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THE PATTERN OF THE EARTH'S MOBILE BELTS

WALTER H. BUCHER
University of Cincinnati

Excessive displacement of the earth's crust has been limited, at least since the later Paleozoic, to well-defined belts, here called the earth's "mobile belts," which are virtually continuous and form a definite and characteristic pattern.

In the first part of this paper, the pattern of these mobile belts is briefly described and analyzed, special weight being given to Haug's hypothetical reconstruction. The essential continuity of these belts points to the conclusions (1) that they are the result of stress conditions in the earth's spheroid as a whole and not of local stresses independent from point to point; and (2) that their pattern, therefore, offers a clue to the mechanics which dominate the major diastrophism of the earth.

In the second part the results of experiments (largely by the author) are presented which show that the pattern of the earth's mobile belts is unlike that displayed (*a*) by wrinkles formed on a thin shell adhering to a contracting core; (*b*) by fractures produced by compression on a thin shell adhering to a contracting core; that it bears a distinct likeness, on the other hand, to the pattern of fractures produced by tension on a thin shell adhering to an expanding core.

BASIC LAWS

The analysis of the structure of the accessible portions of the earth's surface has led to the following generalizations or "laws" which must necessarily form the basis of all systematic thought on the ultimate causes of mountain folding and diastrophic processes in general:

1. The earth's surface deviates everywhere from the ideal form of the ellipsoid through outward (upward) and inward (downward) deflections. Erosion mars and sedimentation masks the details of this condition, at least on land, so that the topography differs in

places conspicuously from the structure which is the expression of this crustal deformation.

2. Two extreme types of crustal elevations and depressions exist with gradations between them.

a) Large portions of the continental and oceanic segments bear elevations and depressions which are, on the whole, not essentially longer than wide, and have vertical dimensions that are small compared with the horizontal. Two graphic terms, "shield" and "basin," have been aptly applied to certain forms of this character. They will here be used for these types in general. The largest of these units are the continental shields and the oceanic basins.

b) In contrast with the shields and basins, the second type shows a distinct linear development with one horizontal dimension decidedly greater than the other. Units of this character will here be designated as "troughs" and "swells."[1]

Dana's terms "geosyncline" and "geanticline" had originally been conceived of merely as "upward and downward flexures of the crust" in contrast to the folds of individual bedded sediments, without a definite distinction between elongated and non-elongated forms. But the intimate association especially of the word "geosyncline," with excessive sedimentation and evidence of tangential stresses early confined its actual use to distinctly linear depressions. This is the sense in which the writer shall use it, that is, as a synonym for "trough," with "geanticline" correspondingly a synonym of "swell," disregarding diverse special meanings that have been attached to these terms by other writers.[2]

3. Excessive displacement of the earth's crust has been limited to troughs and swells, that is, to depressions and elevations of distinctly linear outline.

[1] While in common usage the word "swell" does not necessarily indicate an elevation of elongated form, it recalls the picture of long sweeps of "waves which have outrun the storm," and may therefore properly be used in this special sense.

[2] It should be noted especially that these terms are here used strictly in a descriptive sense. In a mechanical sense, the word "geanticline" was originally conceived by Dana as something very different from the opposite of "geosyncline." In view of the confusion which exists in the use of these terms, it seems best to employ them in a formal sense only, unless one prefers to avoid them entirely, following Suess' example (see footnote on p. 627 of *Face of the Earth*, Vol. IV, or p. 1618 of *Face de la Terre*, Vol. III).

These belts of excessive downward (inward) and upward (outward) radial movements of the earth's surface must be thought of as being more unstable than the rest of the earth's crust. They are themselves, of course, only the outcrops of corresponding three-dimensional bodies, sections of the earth's crust. We shall refer to them as the earth's "mobile belts" rather than "mobile bodies." They are the "mobile features" of the face of the earth, "changing easily or readily in appearance and expression."

4. Troughs and swells are not distributed at random among the shields and basins. On the contrary, they are limited to well-defined belts aligned so as to form a definite and characteristic pattern.

5. The limits of these mobile belts have not been permanent throughout geological time. Since the earlier Paleozoic, they have shifted more or less in such a way that, taken as a whole, later troughs and ranges are essentially parallel to the earlier ones, while in detail the later units intersect the older ones at many places in striking fashion.

6. The processes of "mountain folding" have been confined to geosynclines in which sediments had accumulated to abnormal thickness, that is, to troughs in which both downward movement and sedimentation had taken place more consistently, with fewer interruptions, and generally also at a greater rate than elsewhere.

The importance of the first three and the last of these laws is generally recognized. The same is not true of the other two. This paper, designed to be the first of a series of contributions to tectonic theory, is concerned with the fourth of these laws.

PATTERN OF THE EARTH'S MOBILE BELTS

NEUMAYR'S MAP OF THE YOUNG FOLDED MOUNTAIN BELTS

In 1883 Suess began the publication of his *Antlitz der Erde* in which he demonstrated for the first time the essential continuity of the belts of young mountains in both the old and the new world, giving precision to more or less vague conceptions dating back to Buffon and A. von Homboldt. The first graphical representation of this knowledge seems to be the small map of the young folded mountains in the second volume of Neumayr's *Erdgeschichte* (1887).

It is here reproduced without the needed minor corrections (Fig. 1). It shows the well-known belt encircling the Pacific and departing from it at the Sunda Isles, that other belt which swings into an east-west direction in eastern Tibet and thence extends through the Himalaya Mountains, Persia, Asia Minor, and the Mediterranean countries to the western end of the Atlas Mountains.

As it stands, in its general aspect, this map is simply an expression of fact. The processes of mountain folding have been prac-

FIG. 1.—Neumayr's map of the young folded mountain belts. (*Erdgeschichte*, 2d ed., Vol. II, p. 481.)

tically confined to these belts since the end of the Paleozoic. They have been the most mobile zones of Mesozoic and Tertiary time. But have they been the only mobile zones? They are the belts in which geosynclinal areas have suffered folding and uplift. But we have no reason to think that all geosynclinal belts which may have suffered folding in the Mesozoic or Cenozoic have also been uplifted sufficiently to be accessible, nor indeed that all troughs that came into existence during that time have undergone either folding or uplift.

If we wish to know the pattern of the earth's mobile zones during any limited division of geological time, we must know all the geosynclinal belts of that time.

HAUG'S RECONSTRUCTION OF THE MOBILE BELTS OF THE MESOZOIC AND EARLY TERTIARY

For the Mesozoic and Early Tertiary, Haug has reconstructed the geosynclinal belts in a masterly paper published in 1900.[1] The belts as shown on the map accompanying his paper are here reproduced on a different projection in Figures *2a* and *b*, shaded with horizontal lines. For convenience of comparison, the writer has added: (1) the main areas over which sediments of excessive thickness were laid down during the later Paleozoic (after the Caledonian disturbance; marked by stipling); and (2) some of the conspicuous modern troughs, filled or unfilled, which have existed since the later Tertiary (marked by vertical shading).

For the justification of the belts as reconstructed by Haug the reader is referred to the original paper, to Haug's *Traité de Géologie*[2] and, in a broader sense, of course, to Suess' *Antlitz der Erde*, especially De Margerie's French edition. As drawn, the horizontally shaded belts comprise within their boundaries those parts of the earth's crust within which during Mesozoic and early Tertiary time the formation of troughs was in progress. This does not mean that the whole belt was depressed at all or even at most points, nor that the formation of troughs proceeded simultaneously in all belts or even in all parts of any one belt. They are units, not in a topographic, but in a dynamic sense.

As far as they traverse the land areas, they are essentially continuous. At a few points they abut abruptly against the shores of the oceans. Here Haug has continued them hypothetically in bold curves connecting corresponding loose ends on opposite sides of the waters.

[1] Emile Haug, "Les Géosynclinaux et les aires continentales," *Bull. Soc. Geol. France*, 3e sér., Vol. XXVIII (1900), pp. 617–711.

[2] Emile Haug, *Traité de Géologie*, Paris, 1908–11; especially the "isopic" and paleogeographic maps of Volumes II and III.

HAUG'S CHIEF HYPOTHETICAL LINES

To readers not familiar with the phases of comparative areal geology involved, the hypothetical lines thus added may well appear less justified than they are. There is, for example, the line which connects the High Atlas of Morocco with the West Indian Islands, across the Atlantic Ocean. Just where it should be drawn is uncertain. But the abrupt ending of the folds at the western end of the young folded mountains of Europe suggests a westward continuation of the stresses which created them, while the sudden eastward bend of the Caribbean folds seems to indicate the influence of stresses in a similar direction. Since a dynamic, if not a topographic, relation between these two structural units seems plausible, it may also be granted for the geosynclines from which they have arisen, though it does not follow that a geosyncline actually developed along the whole line. The distribution of shallow water deposits of Jurassic and later Mesozoic age coupled with the distinct European relationships of the shallow water faunas of our Gulf coasts and even of the northern Andes, have led all paleogeographers since the appearance of Neumayr's celebrated map of the seas and lands of Jurassic time to assume the existence of a direct connection of the European and American mediterraneans in a topographic sense.

There is still another argument in favor of this connection which may not be lightly dismissed. Wherever the line of connection between the Alpine and West Indian belts may be sought, it is roughly parallel to the assumed corresponding older link between the paleozoic folds of Cornwall and Brittany on the one hand, and the Appalachian system on the other. The observations pointing to this older connection, which was first recognized by Marcel Bertrand in 1887, are convincing.[1] In view of the fifth of the laws formulated at the beginning of the paper, the parallelism between the two suggested connections appears significant.

The shore of the Arabian Sea cuts across the ranges of Baluchistan, the trough in front of them occupied by the alluvial plain of the lower Indus, and the folds of the Mesozoic rocks of Cutch, on the east side of the Indus lowland. From this point Haug draws a

[1] See Ed. Suess, *La Face de la Terre* (Translation by E. de Margerie), Vol. III, pp. 617 ff. (*The Face of the Earth* in Sollas' translation, Vol. IV, pp. 56 ff.)

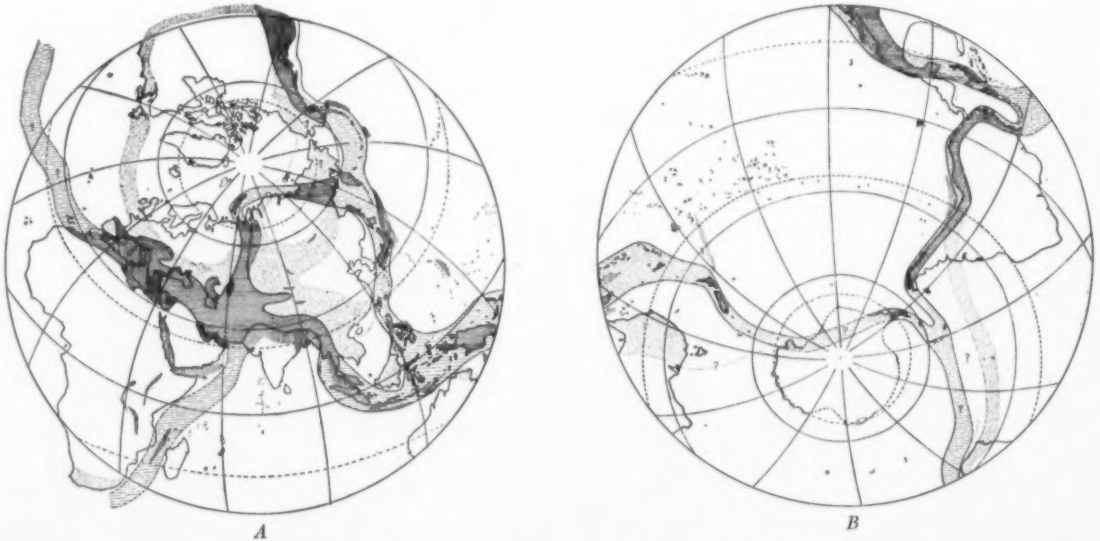

FIG. 2.—Map of the earth, showing mobile belts. *Horizontal shading:* Haug's reconstruction of the geosynclinal belts of the Mesozoic and early Tertiary (here transferred to Lambert's Azimuthal projection). Hypothetical connections of these belts are shown by broken lines. *Stippling:* The main areas over which sediments of excessive thickness were laid down during the later Paleozoic. *Vertical shading:* A number of modern troughs, filled and unfilled, which have existed since the later Tertiary. (The last two added by the writer.)

second hypothetical belt leading through the Strait of Mozambique around the south end of Africa across the southern Atlantic to the circumpacific belt. Here again, the existence of a geosynclinal depression occupying the northern half of this belt from the Strait of Mozambique to the Indus plain, at least during the Jurassic and the later Mesozoic, has long been inferred by paleogeographers. As the "Ethiopean Mediterranean," it figures conspicuously on the paleogeographic maps of Neumayr, De Lapparent, Arldt, and others, separating the "Indo-Madagassian land" from the "Brazilian-Ethiopian continent."

For the southern half of this hypothetical belt, on the other hand, direct evidence is largely lacking. Like its counterpart in the Northern Hemisphere, however, this southern connection appears to be essentially parallel to a strongly suggested older tectonic line which links the paleozoic folds of South Africa with the corresponding folds of the Sierras of Argentina. The striking similarity of the stratigraphic units as well as the diastrophic events exhibited by these two systems of folds on opposite sides of the Atlantic,[1] renders imperative the assumption at least of a dynamic connection between the two.

PATTERN OF THE MOBILE BELTS AS A WHOLE

Let us now review the Mesozoic and early Tertiary geosynclinal belts as a whole, as they appear in Haug's reconstruction (Fig. 2).

Two great belts traverse the Old World. They intersect east of the Caspian Sea forming what we shall call the "cross." Here, in the southeastern half of the area common to both belts, the greatest ranges of Eurasia, Thianshan, Kuen-luen, and Himálaya, and the opposing folds of the Hindu-Kush and Pamir are bound together in a gigantic knot, forming the "roof of the world," a meeting of mountains unique on the face of the earth.

On the opposite side of the earth, the mobile belts form a closed curve, "the ring," as we shall call it, completely encircling the Pacific segment. The ring, to be sure, is an irregular figure and its center does not lie antipodal to the center of the "cross." Nevertheless,

[1] See e.g., J. Keidel, *Anales del Ministerio de Agricultura, Secc. Geol.*, etc., Tom. XI, Num. 3, Buenos Aires, 1916.

the outstanding characteristics of the pattern of the earth's mobile belts, as delineated by Haug, are concisely and graphically expressed by these two words: ring and cross.

RELATION EXISTING BETWEEN OLDER AND YOUNGER BELTS

In the preceding pages reference was made repeatedly to the relation of the late Paleozoic geosynclinal belts to those of the Mesozoic and early Tertiary. A systematic discussion of the relations existing between older and later belts which are summarized in the fifth law of the introduction, would lead beyond the scope of this paper. In passing, however, we shall pause long enough to view in a general way such relations as have found expression on the map (Fig. 2).

In the figure the post-Caledonian geosynclinal belts are represented by the stippled areas, so far as they are not overlapped by belts of later age. The parallelism existing between them and the mobile belts of Mesozoic and early Tertiary time is evident. The older belts appear on the whole to be wider. One branch, since largely abandoned, crosses the heart of Asia in an easterly direction.

Still more interesting are the cases of elongated modern crustal depressions most of which have existed since the later Tertiary. They are shown by vertical ruling and have been added in order to carry the problem of trough formation down to the tangible present. The stratigrapher as well as the structural geologist will do well to ponder over the range of conditions illustrated by these modern "troughs." Where the rate of subsidence has exceeded sedimentation, they are now basins of considerable depth. Here we find typical "bathyal" conditions where the sea has found access, or an enormous thickness of clastic sediments in the process of accumulation, as in the troughs of our Great Basin or in Lake Baikal, where the Angara River has built its fan of coarse gravel and sand out into a depth of over 4,800 feet. Where the rate of depression was slow compared to the rate of sedimentation, or where subsidence ceased long ago, little or nothing is left of the depression, as in the Thar of India and the lowland west of the Yenisei.

If we compare these youngest troughs with the belts of Mesozoic and early Tertiary time, we recognize again the same general

parallelism. The younger troughs, however, are on the whole narrower. (Is it because the formation of such troughs has just begun?) Some strike out beyond the limits of the older geosynclines, taking a step farther in the shifting of the mobile belts. Such is, for instance, the splendid arcuate trough formed by the junction of the Gulf of Aden and the Red Sea, which lies roughly parallel to the double arc of the Gulf of Oman and the Persian Gulf, which in turn closely follow the folded arcs of southern Iran. The arcuate troughs of Central Africa correspondingly follow in general the trend of the hypothetical southern arm of the "cross."

Thus the face of the earth reveals in post-Caledonian time a small number of mobile belts in which excessive up and down movements have taken place along elongated surface elements. From time to time new strips of deformation developed beyond the confines of these belts on one side, while movements ceased temporarily or permanently on parts of the other side. In this way the active portions of these belts slowly shifted.

PATTERN OF THE EARTH'S MOBILE BELTS AS A CLUE TO THE UNDERLYING MECHANISM

As to the pattern of these mobile belts we face three possibilities:

1. The belts at present tangibly exposed on land may be assumed to constitute the whole of the pattern. On this supposition transoceanic hypothetical connections are unjustified. The results of geological synthesis encompassing the globe, which rest on the broad foundation laid by the herculean labors of Suess, permit us to pass over this possibility as highly improbable.

2. The pattern of these belts as far as they are now visible on land may be incomplete and may require hypothetical reconstruction of the concealed or obliterated parts. In such reconstruction, hypothetical additions to the pattern may be limited to lines connecting free ends of the accessible belts, so far as these connections are supported by valid stratigraphic and paleogeographic evidence. This is the basis of Haug's reconstruction.

3. Hypothetical additions to the visible pattern may be made anywhere, and may be founded on diverse reasons, a different reason for each connection, if need be, the resulting pattern to justify

itself subsequently through the understanding it gives of all facts bearing on the mechanics of diastrophism.

In this case the pattern is made to fit a preconceived hypothesis concerning the mechanism of crustal deformation. Among those who have boldly followed this possible mode of attack, the names of Kober and Wegener stand out at present.

Having set aside the first of these possibilities, the instinct of inductive science forces us to turn to the second. Not until we have good reason to believe that it leads nowhere, shall we feel free to turn to the vaguer promises of the third.

Whichever view of the earth's mobile belts we may accept, the continuity of these belts, which shows even in the distribution of the young folded mountains (Fig. 1), points forcibly to two conclusions: (1) That the pattern of these belts is the result of the stress conditions in the spheroid as a whole and not of local conditions independent from point to point. (2) That this pattern, therefore, offers a clue to the mechanics which dominate the major diastrophism of the earth.

This, then, is the question before us: Does a similar pattern arise in a spheroid under any known conditions of stress? The answer is "Yes." To it the rest of this paper is devoted. Before turning to it, however, let us draw a negative conclusion of considerable importance.

PATTERN OF WRINKLES FORMED ON A THIN SHELL ADHERING TO A CONTRACTING CORE

As early as the sixteenth century, Giordano Bruno compared the wrinkles of a drying apple with the mountains of the earth, in a purely formal sense, of course. Near the middle of the last century, Dana and LeConte extended this rather obvious analogy to the mechanism involved. Over a quarter of a century later, Daubrée[1] reported on his "Expériences sur l'action et la réaction exercées sur un sphéroïde qui se contracte par une enveloppe adhérente et non-contractile," in which he observed the wrinkling of rubber balloons coated with paint, wax, gum arabic, and gelatin. Experiments with coated rubber bands seem to have been made first by

[1] *Bull. de la Soc. Géol. de France*, 3e sér., Vol. VII (1879), p. 152. Quoted from A. Daubrée, *Etudes synthétiques de Géologie Expérimentale*, Paris, 1879.

Schardt in 1884. Similar experiments with rubber balloons and rubber bands have repeatedly been made since. The latest experiments with balloons have just been published by R. T. Chamberlin and F. P. Shepard.[1] A number of good photographs of experiments with rubber balloons were published by Toula[2] in 1914.

As far as the pattern of the wrinkles on the spheroid as a whole is concerned, the outcome of these experiments may be summarized as follows:

1. On a uniformly coated balloon a large number of wrinkles of similar dimensions form irregularly intertwined and scattered uniformly over the surface.

2. On a partially coated balloon, on which the coating is applied in the form of bands, the axes of the wrinkles formed trend essentially at right angles to the axes of the bands.

3. On partially coated balloons, on which the coating is applied in the form of irregular patches, the wrinkles form largely and primarily along the edges with their axes at right angles to the outline.

In other words, the pattern of wrinkles formed under the conditions of these experiments is *fundamentally different* from that exhibited by the earth's mobile belts.

This would seem to be sufficient proof that the mechanism underlying the formation of the earth's mobile belts is essentially different from that involved in the deformation of a thin crust of non-contracting material adhering to a contracting core. That is, at least one, possibly several, of the terms describing the condition of the spheroids used in these experiments does not apply to the earth.

But which one is it? Is it the term "thin crust," or in general, "crust" as opposed to "core"? Or "adhering" or "contracting core" versus "non-contracting crust"? Or the very process of "contracting"? By the slow process of elimination we shall know some day.

[1] R. T. Chamberlin and F. P. Shepard, "Some Experiments in Folding," *Jour. Geol.*, Vol. XXXI (1923), pp. 495–96.

[2] Fr. Toula, "Schrumpfungsversuche," *Petermanns Mitt.*, Vol. II (1914), pp. 8–15 (with 24 illustrations on six plates).

We now turn to experiments in which unquestionably a pattern was produced which appears to be comparable to that of the earth's mobile belts.

PATTERN OF FRACTURES PRODUCED BY TENSION ON A THIN SHELL ADHERING TO AN EXPANDING CORE

Experiments on hollow glass spheres.—The following observations were made in the simplest manner possible by allowing water to freeze in hollow glass balls such as are used as ornaments on Christmas trees. The balls were freely suspended in very delicate nets in the open air in freezing weather.

When the temperature drops very gradually below the freezing-point, the first cracks produced assume the shape of a short line bifurcating at both ends. For convenience we will speak of these primary fractures as a "double Y" or simply as "the Y" (Fig. 3). When the glass sphere is opened at this stage it is found to be lined with a layer of ice, consisting of a meshwork of tabular skeleton crystals ending freely in the remaining unfrozen water.

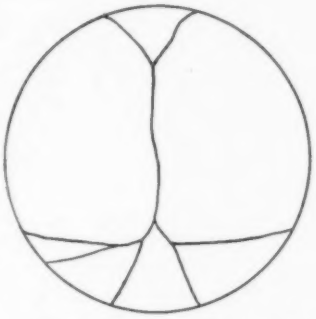

FIG. 3.—Thin spherical glass shell fractured under tension caused by expansion of the interior.

If by further freezing the cracking is permitted to proceed, the branches of the Y bifurcate in the manner illustrated in Figures 4*a* and 4*b*. At the same time they advance toward the opposite side of the sphere, toward the point antipodal to the primary Y. This, however, they generally do not reach. The farther away they extend from the primary Y, the more they tend to be deflected, turning abruptly to one side and continuing in their new direction. In this way one crack may cut across the path of another advancing fracture, terminating its growth; or it may itself come to an end by joining a neighboring fracture. If all initial fractures are thus deflected, as is frequently the case, a more or less large segment is

finally cut out of the sphere by the irregular curve formed by these deflected cracks. The more symmetrically these prolongations of the original cracks develop, the more nearly opposite the center of the Y is this antipodal segment located.

While the main branches show distinctly the tendency to form straight lines, they may develop sharp bends and sudden curves, even "hairpin" curves, and do so especially near the junction with other cracks, which occur chiefly at the boundary of the antipodal segment.

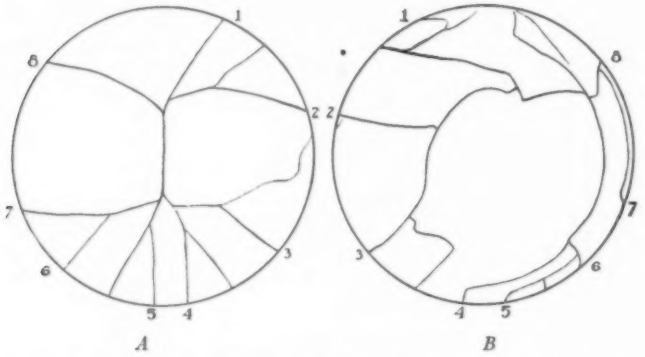

FIG. 4.—Two views of a thin spherical glass shell fractured under tension caused by expansion of the interior, a later stage than that shown in Fig. 3.

If a greater rate of expansion is used, by transferring the water-filled spheres directly into a very cold atmosphere, the essential plan of the fractures remains the same, but undergoes several important modifications: the length of the bar connecting the arms of the double Y, as seen in the former experiments, is found to be shorter, the lower the temperature in which the freezing has taken place. The pattern finally approaches the form of the Cross of Saint Andrew or the letter X, when formed by sudden freezing in very cold weather. The branches bifurcate repeatedly close to the point of crossing, giving rise to a large number of radiating cracks (Fig. 5*a–c*). Most of these, however, remain short and insignificant, while only a few grow far beyond the initial area of cracking and form the

major lines of fracturing. It is largely along these major fractures that an actual separation and outward displacement of the glass shell takes place, exposing the growing ice core. Most of the numerous closely spaced cracks radiating from the central cross remain

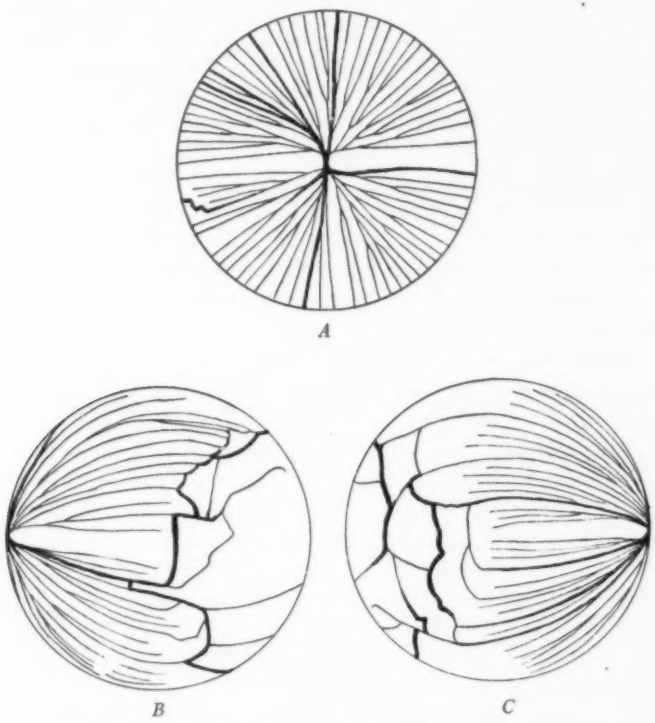

FIG. 5.—Three views of a thin spherical glass shell fractured under tension caused by expansion of the interior, showing modifications when a greater rate of expansion is used.

closed and show no differential movement of the adjoining portions of the glass surface.[1]

This difference between what may be termed the "active" and the "passive" fractures is illustrated in Figure 5. Here, as in the

[1] Unless the process is carried to the extreme.

majority of cases observed, the deflection of the major fractures results in the formation of an irregularly bounded antipodal segment. In a number of cases, chains of arcuate fractures formed along the outline of this segment, as shown in Figure 5*b* and *c*.

None of the observed cases of fracturing, of course, approaches closely the underlying mathematical ideal pattern. Just what this pattern would be, the writer is not yet in a position to state. But all irregularities, such as lack of symmetry in the number and grouping of cracks, and bends and angles in the normally straight fractures, very clearly indicate the individualizing effect of local irregularities in the form, thickness, and substance of the brittle shell. The ultimate deflection of the fracture lines which leads to the formation of the antipodal segment seems, however, to be not wholly dependent on the lack of homogeneity of the material alone.

The influence of such disturbing factors was brought out in the following additional observations.

Experiments on hollow paraffin spheres.—In view of the extreme brittleness of glass, it seemed desirable to repeat these observations with a less brittle substance. When no suitable commercially manufactured hollow spheres could be found, the writer produced hollow spheres of paraffin by pouring hot paraffin into the glass spheres described above and turning them rapidly in all directions while chilling them. The resulting spheres could be made of rather uniform thickness with the exception of the point under the neck-shaped opening. Here the thickness of the paraffin was always excessive, due to a peculiar coarse vesicular structure which always developed at this point. Compared with the glass balls, the paraffin spheres were thicker and less brittle.

When water was allowed to freeze in the paraffin spheres, they showed the same tendency to form the primary double **Y**. But the much greater lack of homogeneity of these spheres produced correspondingly greater irregularities in the pattern of the cracks. In several cases the formation of the double **Y** was thus even completely suppressed or rendered unrecognizable.

The fundamental difference between the fracturing of these paraffin spheres and those of the glass balls lies in the fact that no bifurcating cracks are formed which join the major cracks at highly

acute angles. In general, in most cases very few cracks formed in addition to the primary arms of the double Y and their prolongations (Fig. 6).

The small number of fractures in paraffin in contrast to the very numerous cracks in glass is probably largely due to the lower degree of brittleness. This we may infer from the experiments made by Duparc and LeRoyer, who repeated Daubrée's famous experiments on torsion cracks. When they increased the thickness of the glass plates used in their experiments, the number of additional shearing

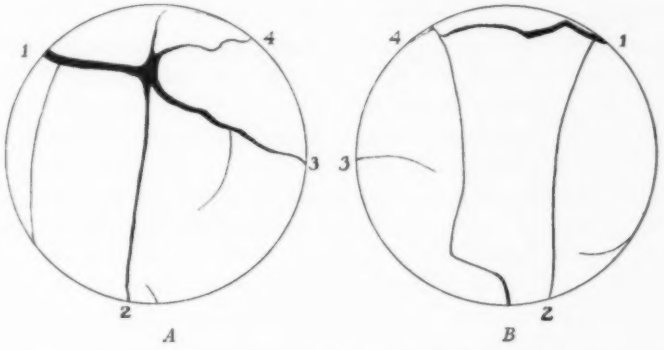

FIG. 6.—Two views of a thin spherical paraffin shell fractured under tension caused by expansion of the interior.

cracks was greatly increased. When, on the other hand, they subjected to torsion ordinary terra cotta plates of dimensions similar to those of the glass plates used, but of a lower degree of brittleness, they obtained only a few master ("tension") cracks.[1]

Summary of results.—We may now summarize the results of our observations:

1. When a hollow brittle sphere is fractured by tension produced through the expansion of the interior, the primary fractures formed assume the shape of a short line bifurcating at both ends (double Y).

[1] Duparc and A. LeRoyer, "Contributions à l'étude expérimentale des diaclases produites par torsion," *Archives des Sciences phys. et nat.* (Genève), 3me sér., Vol. XXII, (1889), p. 307. See also W. H. Bucher, "On the Mechanical Interpretation of Joints," *Jour. Geol.*, Vol. XXVIII (1920), p. 718.

In the case of glass spheres, at least, the stem tends to be short or to be reduced to zero, when the rate of expansion exceeds a certain value. This system of primary fractures may be called the "cross."

2. The number and arrangement of additional fractures, produced by bifurcating or independently, depends on the brittleness of the shell and other physical properties. The more brittle the substance, the more numerous are these additional fractures. They are lacking almost entirely in a substance of the brittleness of paraffin (between 0° and 10° C.).

3. The major fractures tend to turn abruptly after having passed one-quarter of the circumference of the sphere, resulting in many cases in the formation of a conspicuous segment of irregular shape, lying antipodal to the "cross," and bounded by the deflected and joined prolongations of the major fractures. The irregular fractures surrounding the antipodal segment may be called the "ring."

4. The major lines tend to be straight but they may show undulations, angular turns, and even "hairpin" curves along their course.

5. Chains of arcuate fractures form frequently, especially along the "ring."

Comparison with the earth's mobile belts.—The use of the terms "cross" and "ring" at once brings out the surprising similarity of the pattern observed on the glass and paraffin spheres with that exhibited by the mobile belts of the earth's surface. Striking details serve to make the comparison still more impressive. The chains of arcuate fractures, especially where they lie on one side of the "ring," vividly recall the island arcs of Eastern Asia, von Richthofen's "Zerrungsbogen." The hairpin curves occasionally seen on glass spheres, chiefly at the junction of two fractures, closely imitate the strange curves which connect the northern Atlas with the Betic Cordillera, the Caribbean Islands with the Cordilleras of the two Americas, and the Andes of Southern South America with the South Shetland Islands past South Georgia, the Sandwich, and the South Orkney Islands.

The reading of Suess' *Antlitz der Erde* cannot fail to create the strong impression that in the structure of the continents major lines of deformation which are clearly the product of tension are generally curiously independent of others which have resulted from compression. The idea naturally suggests itself that conditions of

tension might have alternated with compression in the earth's crust. It is not surprising, therefore, to find that such a view has already been advocated by Rothpletz.[1]

The temptation to select from the vast array of facts, inferences, possibilities, and assumptions which constitute the bewildering literature on diastrophism, as many items as would fit such a hypothesis, was so strong that the writer promptly yielded to it in his first presentation of the experiments here related before the Geological Society of America at Chicago in 1920.[2]

That paper was never published. For the time being the discussion of the underlying hypothesis has been laid aside. We are not ready to judge successfully the "truth" of this or any one of the number of hypotheses that seem to offer a possible solution to the problem of the earth's major diastrophism. We need to assemble before us, in logical order and terse form, all materials that bear on this complex problem, before we can hope to detect among the many possible solutions, known and unknown, the one which satisfies them all, and therefore is "true." The present paper, and others to follow, aim to contribute to that end.

The final result of the experiments related above, in so far as they have a bearing on the question of major diastrophism, may be formulated as follows: The pattern of fractures produced by tension in a thin and not too brittle spherical shell shows the "cross," and tends to show the "ring" characteristic of the pattern of the earth's mobile belts as interpreted by Haug.

At once the question arises: Is tension necessary for the production of this pattern, or does compression yield similar results? To find an answer, another series of experiments was undertaken. This time the writer enjoyed the co-operation of his colleague Dr. R. C. Gowdy,[3] who shares in the following account of the experiments.

[1] A. Rothpletz, "Über die Möglichkeit, den Gegensatz zwischen der Kontractions- und Expansions-theorie aufzuheben," *Sitzungsber. Münchener Akad. Wiss.* (1902), pp. 311–25.

[2] W, H. Bucher, "On the Probable Cause of the Localization of the Major Geosynclines" (Abstract), *Bull. Geol. Soc. America*, Vol. XXXII (1921), p. 75.

[3] Of the Physics Department of the University of Cincinnati, to whom the writer wishes to express his sincere thanks at this place.

PATTERN OF FRACTURES PRODUCED BY COMPRESSION ON A THIN SHELL ADHERING TO A CONTRACTING CORE

Experiments on hollow glass spheres.—The apparatus employed for placing the spheres under pressure was constructed from a piece of steam pipe 6 inches in diameter and 6 inches long, fitted with malleable iron-pipe caps for ends. The lower end was screwed on firmly, but the upper cap was removable for the introduction of the spheres. The upper cap was provided with an air vent and filling valve and the lower cap was fitted with a drain valve, pressure gauge, and screw plunger by means of which pressure could be applied. Pressures over 200 pounds per square inch were attainable, but none of the spheres required over 100 pounds to produce failure, some breaking at pressures of 25 to 30 pounds.

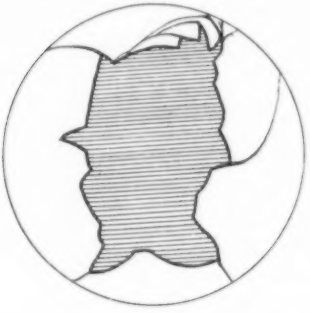

FIG. 7

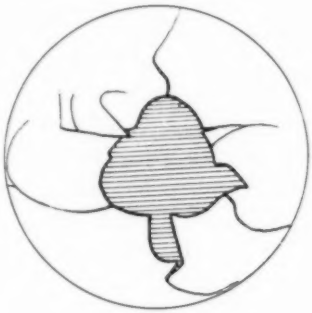

FIG. 8

FIGS. 7–8.—Thin spherical glass shells fractured under compression (without capillary attachment).

In the first series of experiments, thin glass spheres of the same kind that was used in the experiments on tension were put under pressure. The first trials showed that the use of such extremely brittle and thin glass spheres was possible only if a means could be found to prevent their complete disruption. Three methods were used to that end:

1. The glass spheres were covered externally with a thin coat of collodion and nearly but not quite filled with water.

Figures 7, 8, and 9 illustrate the condition of the spheres after failure had occurred. They show large broken areas and, radiating

from them, a few cracks of varying length which do not display a distinct tendency to branch. The form of the fractured areas led us to consider them as secondary, due to the sudden inrush of water at the moment of rupture. They destroyed beyond the hope of recognition all traces of the primary fractures. We decided, therefore, to attempt to eliminate them as far as possible.

2. The spheres were filled with a solution of gelatin beaten to a foam. The spheres fractured as before. Better results were obtained through a device introduced by Dr. Gowdy.

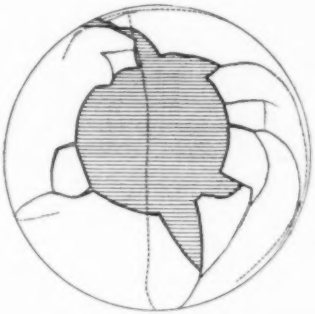

FIG. 9.—Thin spherical glass shell fractured under compression (without capillary attachment).

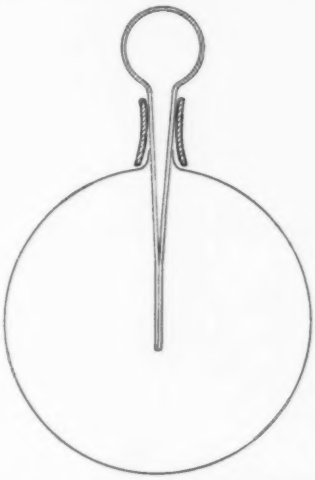

FIG. 10.—Diagram showing thick-walled bulb with capillary tube attached to thin-walled glass sphere.

3. The spheres were completely filled with water and a thick-walled bulb with a fine capillary stem was attached to the neck of the globe by means of a short section of rubber tubing, as shown in Figure 10.

The fine capillary tube allows a gradual adjustment of pressure, and failure occurs without great violence.

Figures 11, 12, and 13 illustrate the results obtained by this method. A completely destroyed area still remained, but on the whole it was smaller than in the preceding experiments. The cracks, however, which radiate from this area in these experiments show a

strong tendency to bifurcate and branch out much in the same manner as the cracks in spheres broken under tension.[1]

This similiarity seemed to us most significant. We inclined to the view, which later proved to be erroneous, that it indicated that the pattern of fractures produced under compression is essentially identical with that produced under tension. It seemed to us at that time that if we could but eliminate the destruction of the central area, we should find the double Y or "cross" fracture at the point of initial rupture.

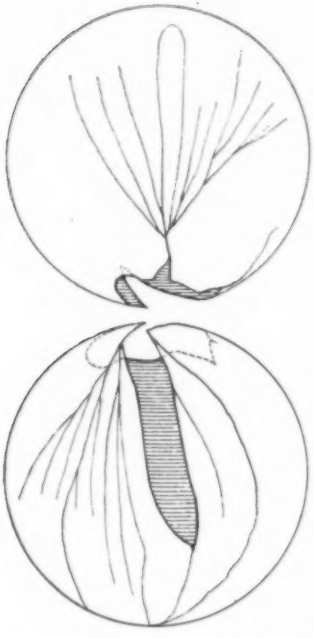

FIG. 11.—Thin spherical glass shell fractured under compression (with capillary attachment).

It was disconcerting, however, to find the planes of fracture everywhere normal to the surface as they would form by flexure or tension but not by compression. In glass the shearing planes always form an acute angle with the direction of compressive stress. In our glass spheres they should have been, therefore, nearer the tangential than the normal direction.

Experiments on hollow paraffin spheres.—A last series of experiments showed us that we had completely misunderstood the nature of the fracturing of the glass spheres under pressure. In these experiments paraffin-coated rubber sponge balls were used instead of the extremely brittle glass balls. By removing the smooth surface of the ordinary commercial rubber sponge balls so as to expose the vesicular texture of the spongy interior, the paraffin coating was fairly well interlocked with the body of the ball.

[1] Figure 11 was drawn especially to illustrate the resulting pattern of cracks. It should be noted that the true shape of the central area cannot be recognized in this position of the sphere.

In the experiments warm water was used to reduce the brittleness of paraffin sufficiently. Figures 14, 15, and 16 illustrate the results.

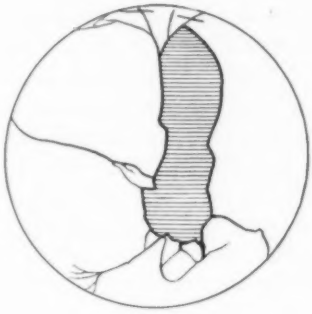

FIG. 12

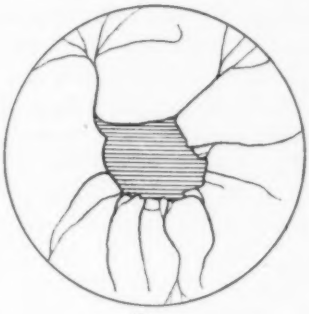

FIG. 13

FIGS. 12 AND 13.—Thin spherical glass shells fractured under compression (with capillary attachment).

FIG. 14

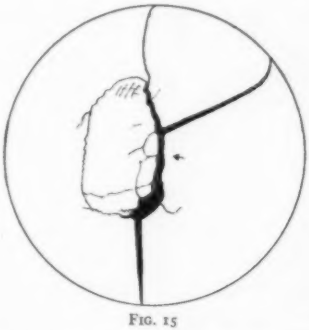

FIG. 15

FIGS. 14 AND 15.—Thin spherical shells of paraffin fractured under compression

In the typical cases shown in the first two figures, three types of fractures can readily be distinguished:

1. Fractures formed under compressive stress. They occupy an oblique position and are strongly slickensided.

2. More or less semicircular fractures bounding segments which flank the initial compression ruptures on one or both sides. The

more or less intensely shattered segments have clearly been broken from the spheres by the local bending resulting from the inclined position of the fracture planes. The semicircular fractures are accompanied by a delicate pattern of two conjugate joint systems. In fact they themselves consist of numerous little steps alternating. in the direction of one and then of the other of these joint systems, producing a zigzag line. Such conjugate joint systems are characteristically associated with torsional stresses such as must arise where downward bending combines with tangential pressure.

Combined, these semicircular fractures circumscribe a central area which has become detached from the rest of the sphere and is clearly identical with the central area encountered in the fracturing of the glass spheres.

FIG. 16.—Thin spherical shell of paraffin fractured under compression.

3. Radiating from this central area are a few cracks, widely gaping, with sides normal to the surface and lacking every trace of slickensides. They can only have been formed under tensional stresses under complete absence of pressure. There can be no doubt that they correspond to the bifurcating cracks which were seen radiating from the central area in the glass spheres. They do not merely resemble, but are, tension cracks. Our first interpretation was wrong. The fracturing of thin spherical shells under pressure must proceed as follows.

The compressive stress is first relieved by the formation of an inclined shearing plane. The hanging wall moves up along this inclined plane and the foot wall is depressed. This introduces a bending moment which affects only relatively small more or less semicircular areas adjacent to the initial fracture. The resulting torsional strains are relieved by the formation of the familiar pattern of joint systems in substances which are not too brittle. In such cases the semicircular marginal fractures along which the bent areas finally detach themselves from the body of the sphere show in detail a characteristic zigzag shape where they utilized these pre-

existing joint planes. Very brittle substances, such as glass, do not generally form shearing planes under torsion but break very largely along tension fractures. In our experiments with glass spheres the marginal cracks of the central areas of fracture, therefore, did not show such zigzag outline and stood essentially normal to the surface.

This is all that happened in our experiments under pressure. The formation of a more or less compact area is the only essential form of fracturing of a sphere under pressure. There is no evidence of a single crack radiating outward from this area having formed under pressure in any of our experiments.

The radiating cracks which were, nevertheless, always found on our spheres, clearly are tension cracks formed as the result of internal expansion after release of pressure. In our experiments with glass spheres we found that the tendency of these tension cracks to bifurcate was the more pronounced the smaller the collapsed central area was. This area, however, was the smaller the slower the compression of the sphere proceeded. That is, the tension cracks developed best in spheres completely filled with water from which the water had to be forced into an attached small thick-walled bulb through a capillary.

An interesting departure from the usual pattern of fractures is illustrated in Figure 16. Here three fractures had formed simultaneously, starting from one point. As was pointed out before, this should be the normal condition if the substance of the spheres were strictly homogeneous. The water in this experiment had been warmer than usual, causing the paraffin to bend along the fractures and preventing the chipping out of segments. Had the paraffin been brittle enough to cause the bent-up triangles to break off, the resulting central area should have been of triangular shape. This is obviously what happened in the case of collapsed central areas of threefold symmetry like the one illustrated in Figure 8.

Summary of results.—The decisive result of these experiments on spheres under pressure may be formulated as follows.

Pressure exerted on the outside of thin-walled hollow spheres does not produce a pattern of branching fracture lines comparable to that formed under tension. A single compact area is detached from the body of the sphere bounded on the outside by fractures produced under torsional strain, and traversed on the inside by one or several

inclined thrust planes causing it to be shattered into numerous fragments.

Or, viewing the experiments in their bearing on the problems of diastrophism: The pattern of fractures produced by pressure alone on thin-walled spheres of non-contracting material surrounding a contracting interior is fundamentally different from that of the earth's major mobile belts.

GEOLOGICAL OUTLOOK

For the time being, we may, therefore, revert with greater confidence to the observation formulated on page 283: The pattern of fractures produced by tension alone in a thin and not too brittle spherical shell shows the "cross," and the "ring" characteristic of the pattern of the earth's major mobile belts as interpreted by Haug.

A third possibility still exists. The two conditions, pressure and tension, may alternate. The temptation is great to speculate on this possibility. But it is too early.

Having seen that pressure alone does not suffice to produce the pattern of the earth's mobile belts, we must squarely face the question what "tension" may mean in the earth's crust, if indeed "tension" is the only factor capable of producing such a pattern in a body like the earth.

Since the writer is engaged at present in nothing more than the accumulation of pertinent data for use in the ultimate search for a solution of the problem of the earth's major diastrophism, he is not concerned with an answer to this question now. It so happens, however, that the term "shell of tension" has long played a conspicuous rôle in geophysics in connection with the mathematical analysis of the distribution of temperatures and pressures in a cooling solid earth. In this country it was Daly who built an interesting hypothesis of diastrophism on it.[1] It seemed desirable, therefore, to re-examine the mathematical and physical basis of this conception. The writer's colleague and friend, Dr. L. Brand, has kindly consented to co-operate in this inquiry. He has taken upon himself, above all, the mathematical part of this task. The joint paper containing our findings will constitute the second paper of this series.

[1] R. A. Daly, "Abyssal Igneous Injection as a Cause and as an Effect of Mountain Building," *Amer. Jour. of Science*, Vol. XXII (172) (1906), pp. 195–216; *Igneous Rocks and Their Origin*, 1914, pp. 174–86.

THE TEMPERATURES OF HOT SPRINGS AND THE SOURCES OF THEIR HEAT AND WATER SUPPLY. II[1]

RELATION OF CRYSTALLIZATION TO THE WATER CONTENT AND VAPOR PRESSURE OF WATER IN A COOLING MAGMA

GEORGE W. MOREY
Geophysical Laboratory, Carnegie Institution of Washington

An igneous magma is a liquid composed of non-volatile constituents such as the silicate minerals and volatile substances far above their critical temperatures. Of these, water is considered to be present in preponderant amount, while the other volatile components, such as sulfur, boric acid, phosphoric acid, hydrofluoric acid, hydrochloric acid, and carbon dioxide, are present in such amounts that they are to be regarded as accessory or as negligible. In the following discussion I shall consider water as the typical and preponderant volatile constituent, realizing that the other constituents will not materially affect the discussion, with the exception of cases in which they exercise a specific chemical effect. It is desirable to consider the rôle played by the volatile components during the period when the cooling magma is depositing the non-volatile components first in the form of magmatic deposits proper, then in the form of pegmatites, then through various intermediate phases, until the water, still containing in solution some of the accessory volatile material, as well as small quantities of non-volatile substances, appears as a hot spring.

Consider the magma in an initial condition in which the volatile material is but a small proportion of the total mass. The non-volatile material will be essentially liquid; there may have been an initial separation of minerals such as magnetite, but the mass as a whole is a liquid containing but a small amount of volatile material, at a temperature not much below that of anhydrous

[1] Continued from *Journal of Geology*, XXXII, 225.

fusion of the complex mineral system. Under these conditions, while the temperature may be high, the vapor pressure of the volatile material will be comparatively low. In this connection a sharp distinction is to be drawn between the total pressure existing on the liquid, corresponding to the pressure of the overlying rocks, and the vapor pressure of the volatile constituents of the magma. The vapor pressure corresponds to the pressure generated inside a boiler; the total pressure is the blow-off pressure determined by the safety valve.

Under the initial conditions the vapor pressure of the dissolved water will not be large, and the freezing-point lowering of the silicate minerals resulting from the small proportion of water will be small. Laboratory experiments have shown, however, that even under a vapor pressure of water of only one atmosphere liquid silicates take up appreciable amounts of water, with a resulting determinable depression of their freezing point. As the pressure is increased in the laboratory experiments, more and more water is dissolved, and the freezing point is progressively lowered. But in systems of this type, composed of both volatile and non-volatile components, we have the unusual condition that the vapor pressure of the system does not decrease with decreasing temperature, as is the almost universal rule, but on the contrary increases as the temperature falls. The reason is not difficult to see; as the temperature of the magma falls, some of the non-volatile material crystallizes, and the water becomes concentrated in the residual liquid. But to increase the water content of the fused silicates necessitates an enormous increase in the pressure required to hold the water in the solution.

This increase in pressure, however, does not continue indefinitely. We have to consider the effect of two opposing tendencies. One of these, the concentration of volatile material resulting from the crystallization of the non-volatile substances, tends to increase the vapor pressure of the solution; the other, the decrease in equilibrium temperature resulting from the increased lowering in freezing point of the solutions with increase in water content, tends to decrease the vapor pressure. Initially, the first effect preponderates, and

the vapor pressure of the saturated solution rises rapidly as the magma cools, but before the volatile material becomes preponderant in amount, in fact probably before the water content reaches 20 molecular per cent, the vapor-pressure curve reaches a maximum, and, on further cooling, the vapor pressure of the solution decreases with falling temperature.

This maximum pressure is fixed by the composition of the liquid phase. Further crystallization, either in place or after transportation to another place, can only result in a decrease in pressure; while an increase in temperature, if accompanied by re-solution of the precipitated material, will also result in a diminution in pressure. The magnitude of the maximum pressure is an interesting subject of inquiry, but unfortunately we have at present no conclusive experimental evidence. It is to be emphasized that experiments such as are now being carried out at the Geophysical Laboratory, with systems of only four or five components, only one of which is to be regarded as volatile, can only yield information as to a possible upper limit of pressure. Actual magmas will contain not only a wider variety of non-volatile components, each of which will tend to diminish the pressure, but also a quantity of other volatile substances, such as sulfur and boric acid, which will exercise an appreciable effect on the pressure.

The temperature corresponding to the maximum in the pressure curve is likewise at present a matter of guesswork, and it also will depend on the composition of the liquid. In all probability the period of formation of pegmatites corresponds roughly to the period of the maximum pressure, or to the initial portion of the period of decreasing pressure; in that case the temperature would probably be about 575°. In a laboratory study of mixtures of orthoclase, quartz, and water, we have been able to obtain liquid solutions at 600° and a water vapor pressure of approximately 700 atmospheres, with but a slight excess of potash. It is probable that to dissolve completely a mixture of one part of orthoclase to two parts of quartz at 600°, in the system composed of the pure components, a water-vapor pressure of 1,500 to 2,000 atmospheres would be required, but the system as it exists in nature is not a simple one,

and, indeed, probably contains enough additional material of varied character to diminish the pressure of the saturated solution to that of the solution we have obtained with excess potash.

On further cooling, crystallization will continue, but this will become of a different type. The earlier crystallization is essentially of silicate minerals; the later stages are characterized by the beginning of crystallization of the accessory components as shown by minerals of complicated structure, of such minerals as the fluorine-bearing tourmaline and fluorite, apatite, and perhaps cassiterite, and other high-temperature vein minerals. Important differentiation of sulfide minerals may take place at this period. The temperature may be roughly between 300 and 500°, but it is the pressure relations I wish particularly to stress. The liquid now contains far more water than at the period of maximum pressure, but the vapor pressure of this water will have been much reduced, primarily as a result of the reduction in temperature. Moreover, although the liquid is unquestionably mobile enough to penetrate cracks and fissures with ease, it will still be far removed from the relatively pure water issuing from even the most heavily mineralized hot springs. The vapor pressure of the water will be lowered by the dissolved material, and at the critical temperature of water the solution will have a pressure much less than that of pure water at its critical point.

The critical relations of systems containing non-volatile and volatile components I have not discussed, because they do not concern us in connection with natural magmas. I realize that this is in conflict with the views of most writers who have discussed the subject, but nevertheless I have no doubt as to the correctness of the statement. In the first place, the critical point of water, at 374° C and 200 atmospheres, is characteristic only of pure water. Addition of any soluble substance will raise the critical temperature of the solution, just as addition of any soluble substance raises the boiling point of the solution. Furthermore, as the cooling magma eliminates one component after another by crystallization, more or less completely, the residual magma will at all times contain enough material of lesser volatility, such as the borates, phosphates, silico-fluorides, fluorides, and chlorides, to hold the components of

greater volatility, mainly water, in solution. In other words, the critical phenomena are never shown by the saturated solutions formed by the cooling magma, and the critical curve of these liquids is never cut by the solubility curve. The liquid phase at any stage would have to be heated to a much higher temperature to show critical phenomena.

By the time the residual magmatic solutions have cooled to a temperature below the critical temperature of water, the greater portion of the original magma will have crystallized. On further cooling the aqueous solution becomes more and more dilute, until we come to the final period of hot-spring activity. But it is to be emphasized that the entire cooling of an igneous magma, from the initial condition in which the magma consists essentially of non-volatile substances, with but a small amount of water, to the dilute solutions given off by hot springs, is a continuous process. If the magma is cooling under a competent crust, the non-volatile substances crystallize from a liquid containing more and more water, and at all times in the process there is a liquid phase. The liquid exerts over the entire range of cooling a vapor pressure, which at first increases rapidly to a maximum, then decreases, and at all times the vapor pressure is not that of water at the temperature in question, but of an aqueous solution, in which the vapor pressure of the water is much reduced by the dissolved material. In natural magmas critical phenomena probably play no part.

ORIGIN OF THE THERMAL SPRINGS OF NEVADA, UTAH, AND SOUTHERN IDAHO

OSCAR E. MEINZER
U.S. Geological Survey, Washington, D.C.

In the fifteen years in which I have been concerned with investigations of ground water in the arid regions of the United States, I have observed many of the thermal springs in these regions. The present brief paper relates to the thermal springs of the basin-and-range province in Nevada, Utah, and Idaho and of adjacent parts of Idaho. Its purpose is to make some broad generalizations

in regard to the geology of the thermal springs in this region, and in regard to the bearing of the geology on the source of the thermal water. A few examples are given to illustrate these generalizations, but the generalizations themselves are based on a large amount of data that cannot be given in a brief paper of this kind. The discussion relates to both hot and warm springs—that is, to all springs whose temperature is appreciably above the mean atmospheric temperature of the vicinities in which the springs occur.

RELATION OF SPRINGS TO VOLCANIC ROCKS

In 1876 Gilbert[1] published a map of the United States, giving the hot-spring localities known at that time. This map shows that all except a few of the thermal springs are in the western mountain region (Rocky Mountain system, Intermontane plateaus, and Pacific mountain system). A more detailed map of the thermal springs in the United States is at present being compiled by Norah E. Dowell, of the United States Geological Survey, but it will not differ essentially from Gilbert's map in the general distribution of the thermal springs. The Tertiary and Quaternary volcanic rocks are also nearly all in the western mountain region, in which they are widely distributed and cover large areas. Because of this general coincidence of thermal springs with volcanic rocks it is sometimes assumed that the hot- or warm-spring water is commonly derived from volcanic (extrusive) rocks which have not yet cooled off. In fact, however, a large part of the thermal springs in Nevada, Utah, and southern Idaho do not issue from Tertiary or Quaternary volcanic rocks, and some of those that do issue from these rocks are known to obtain their thermal water from underlying older formations.

In southeastern Idaho there are numerous thermal springs, but very few, if any, are found in the Snake River plain, which is underlain by basalt that ranges in age from mid-Tertiary to Recent; all or nearly all occur in the surrounding region and issue from older rocks, such as early Tertiary rhyolite, Cretaceous granite, and

[1] G. K. Gilbert, *U.S. Geol. Surveys West of the 100th Meridian*, Vol. III, Pl. III, 1876.

Paleozoic quartzite, limestone, and chert (Fig. 1). Piper[1] has recently made an artesian-water survey of the Goose Creek basin, which borders the Snake River plain on the south. In this basin Paleozoic rocks, greatly faulted and otherwise deformed, are unconformably overlain by a Tertiary formation of rhyolite, tuff, and sedimentary beds, which is also faulted, as shown in Figure 2. A little warm water issues from the Tertiary formation, and warm

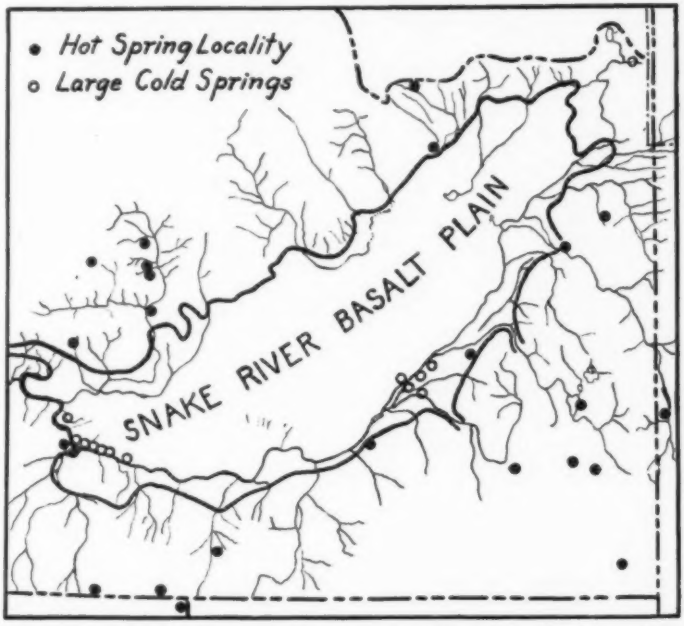

FIG. 1.—Map of southeastern Idaho showing relation of thermal springs and large cold springs to the Snake River basalt plain. Compiled by H. T. Stearns.

water has been struck in several artesian wells drilled into this formation, but most of the thermal springs issue from the Paleozoic rocks. Evidently the warm water in the Tertiary formation was derived from the underlying older rocks. A similar relation of the

[1] A. M. Piper, "Geology and Water Resources of the Goose Creek Basin, Cassia County, Idaho," *Idaho Bureau of Mines and Geology, Bull. 6* (1923).

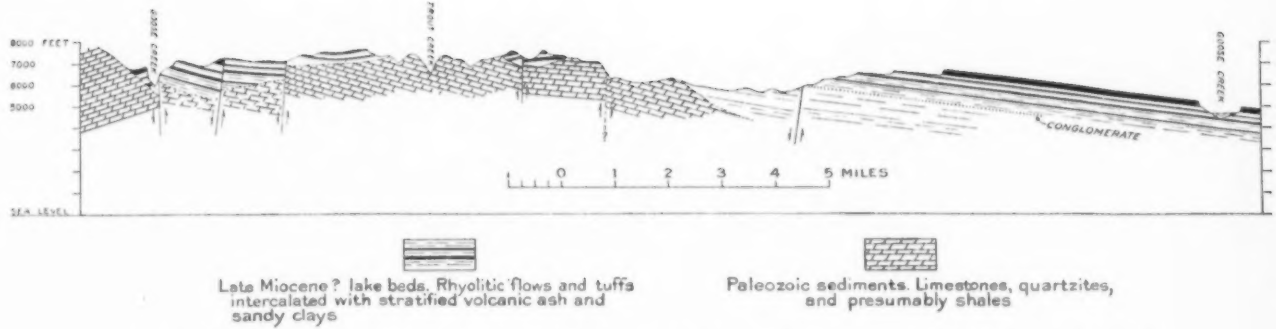
8000 FEET
7000
6000
5000
SEA LEVEL
CONGLOMERATE
0 1 2 3 4 5 MILES
Late Miocene? lake beds. Rhyolitic flows and tuffs intercalated with stratified volcanic ash and sandy clays
Paleozoic sediments. Limestones, quartzites, and presumably shales

FIG. 2.—Geologic section in Goose Creek Basin, Idaho. After A. M. Piper, *Idaho Bureau of Mines and Geology, Bull. 6*, Pl. I

thermal water to older rocks overlain by Tertiary volcanic rocks is illustrated by the Spencer Hot Springs, Nevada (Fig. 3).

RELATION OF SPRINGS TO ARTESIAN STRUCTURE

It is generally believed that thermal springs which do not issue directly from hot volcanic rocks owe their high temperatures to artesian structure that causes the ground water to descend to

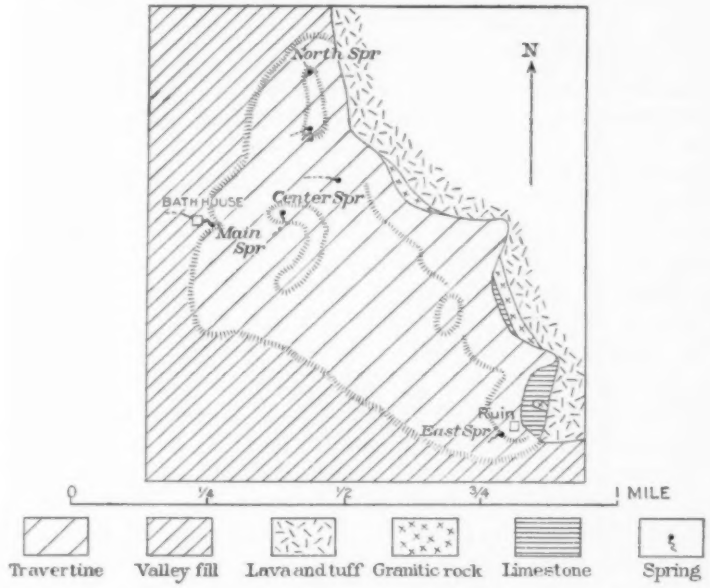

FIG. 3.—Map of the vicinity of the Spencer Hot Springs, Nevada. (*U.S. Geol. Survey, Water-Supply Paper 423*, Fig. 6.) The lava and tuff are Tertiary, and the limestone is doubtless Paleozoic. The granitic rock is much older than the lava.

great depths. However, most of the thermal springs in Nevada, Utah, and southern Idaho do not issue from rocks that have definite artesian structure, and some issue from granite that almost certainly has no artesian structure. In the Goose Creek Basin (Fig. 2), the Tertiary beds form an artesian system that yields warm water, but the artesian structure apparently has nothing to do with the

rise of the warm water through the underlying older rocks. Moreover, most of the warm water issues directly from the older rocks, which are so much broken and deformed that they seem to lack entirely the structure of an artesian basin. Another typical example of the lack of artesian conditions is afforded by the Darrough Hot Springs, in Big Smoky Valley, Nevada. These springs are on an alluvial fan on the west side of the valley and issue from bowldery valley fill, but their water doubtless comes from the underlying rock. The mountains on both sides of the valley are composed mainly of greatly deformed Paleozoic quartzite, limestone, slate, and schist, and rather old Tertiary rhyolite and tuff. The mountain front on the west side of the valley is essentially a fault scarp produced by extensive faulting in Pliocene and Quaternary time. Obviously such a structure would be considered entirely unfavorable for artesian water.

RELATION OF SPRINGS TO FAULTS

Many of the thermal springs in Nevada, Utah, and southern Idaho are definitely related to faults. The relation of the Darrough Hot Springs to a major fault is quite typical of the thermal springs of the region. The close relation of the springs, largely thermal springs, to faults in northwestern Nevada is shown in the map (Fig. 4), which is based on Russell's work.[2] The section shown in Figure 2 also suggests a causal relation between springs and faults. The relation of thermal springs to faults in the basin-and-range province has been clearly recognized by Russell and other geologists.

AGE OF THE SPRINGS

The geologic relations of the thermal springs in Nevada, Utah, and southern Idaho indicate that most of these springs are not ephemeral features, but have been in existence a long time. It is believed that in the Goose Creek Basin most of the volcanic rock was extruded during the Miocene epoch, and much of the faulting in the Paleozoic rocks preceded the extrusion. Moreover, the

[1] O. E. Meinzer, "Geology and Water Resources of Big Smoky, Clayton, and Alkali Spring Valleys, Nevada," *U.S. Geol. Survey, Water-Supply Paper 423*, p. 89.

[2] I. C. Russell, "Geological History of Lake Lahontan, a Quaternary Lake of Northwestern Nevada," *U.S. Geol. Survey, Monograph 11*, Pls. III and VIII.

main features of the topography are by no means recent. In Big Smoky Valley the faulting commenced in the Tertiary, and the volcanic rocks were extruded before the faulting occurred. The faults shown in Figure 4 were all formed before the close of the Tertiary period. The conclusion seems warranted that most of the thermal springs in the region came into existence before the close of the Tertiary, although their specific locations have doubtless changed from time to time.

QUANTITY OF WATER DISCHARGED BY THE SPRINGS

Data on the discharge of thermal springs are very inadequate. The total quantity of thermal-spring water that is discharged to the surface in the region under consideration is considerable, yet not so very great as compared with the total quantity of non-thermal water discharged through springs or by evaporation and transpiration, nor as compared with the volume of rock from which the water might be derived. Moreover, many of the largest thermal springs have temperatures only slightly above normal, suggesting admixture of much non-thermal water near the surface.

SUMMARY

In summary it may be said that the thermal springs of Nevada, Utah, and southern Idaho are largely related to faults that came into existence before the close of the Tertiary period; that they occur in the same general areas with large quantities of volcanic rocks—chiefly Tertiary, but in part Quaternary—but that many of them are not closely related to the volcanic rocks and do not derive heat from them; that they cannot generally be attributed to artesian structure; that they have been in existence a long time but have comparatively only a moderate discharge.

CONCLUSIONS AS TO SOURCE OF THERMAL WATER

The relation of these springs to large faults and their common lack of relation to volcanic rocks indicate that the thermal water of the region comes largely from considerable depths. Though the lavas that have been extruded in immense quantities during the Tertiary and Quaternary periods are demonstrably not the source

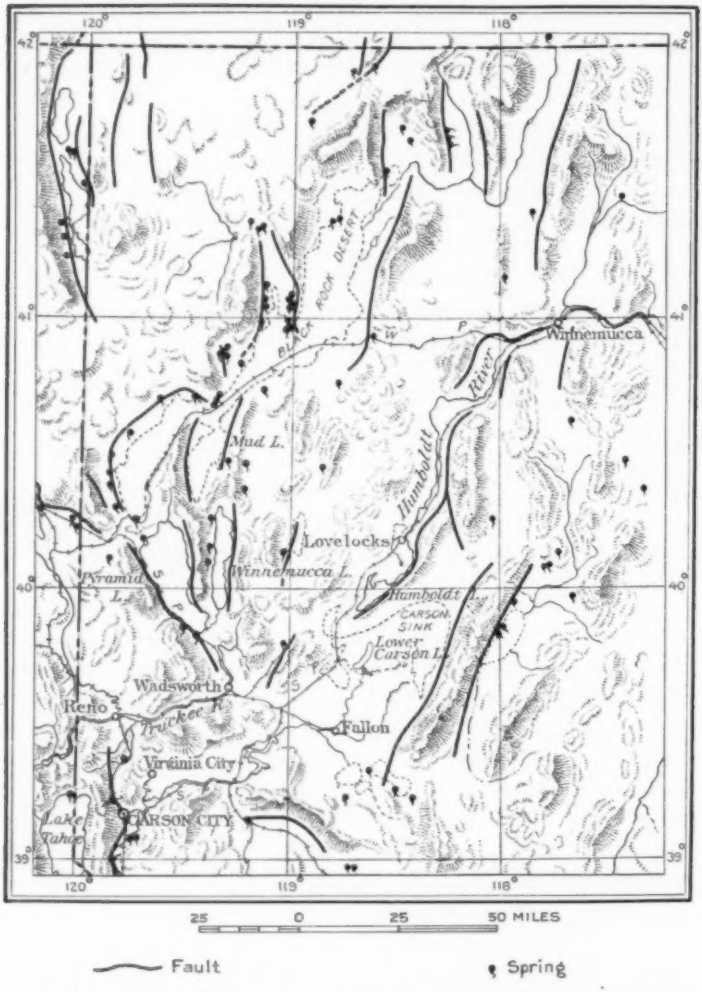

FIG. 4.—Map of the northwestern part of Nevada, showing relation of springs (largely thermal) to pre-Quaternary faults. (After I. C. Russell. See *U.S. Geol. Survey, Water-Supply Paper 489*, Fig 69.)

of the heat of many of the thermal springs, they indicate the existence of underlying parent magmas, to which the major faults may extend and from which the heat of the thermal water may be derived. There appear to be two possible explanations of the thermal springs that have deep sources, such as the springs in the Paleozoic rocks of the Goose Creek Basin. They may be due to the circulation of meteoric water somewhat as in a hot-water heating system, without definite artesian structure, or they may be due to the rise of juvenile water given off by underlying magmas. There is apparently no decisive evidence available for determining which of these processes is actually taking place or whether perhaps both are taking place. The juvenile-water theory is regarded by many geologists as less conservative than the meteoric-water theory, but the deep source of these springs and the general absence of artesian structure seem favorable to the juvenile-water theory. A more serious quantitative study than has hitherto been made of the thermal water and thermal energy that has been emitted by these springs would doubtless throw light on the relative merits of these two theories.

HOT SPRINGS OF THE VALLEY OF TEN THOUSAND SMOKES

E. G. ZIES
Geophysical Laboratory, Carnegie Institution of Washington

The Katmai region of the Alaskan peninsula presents considerable interest on account of the great eruption of Mount Katmai in 1912 and the associated fumarolic activity of the Valley of Ten Thousand Smokes discovered by Professor R. F. Griggs in 1916. This region has been investigated by the members of several expeditions sent out by the National Geographic Society, one of which was accompanied by a party from the Geophysical Laboratory. The reader is referred to the published accounts for the detailed description of the general geological and chemical features of this region.[1]

[1] R. F. Griggs, "The Valley of Ten Thousand Smokes," *Nat. Geog. Mag.*, Vol. XXXI (1917), pp. 12–68; Vol. XXXIII (1918), pp. 115–69; "Are the Ten Thousand Smokes Real Volcanoes?" *Ohio Jour. Sci.*, Vol. XIX (1918), pp. 97–116; "The Great Hot Mudflow of the Valley of Ten Thousand Smokes," *ibid.*, pp. 117–42; "The

The fumaroles of the Valley of Ten Thousand Smokes were investigated in 1919 by Allen and Zies.[1] They found that the temperatures of the gases escaping from the fumaroles ranged from 97° to 645° C. and that the chief constituent of these gases was steam, which was present to the extent of about 99.9 per cent. They also found that even though the activity was vigorous, as indicated by the velocity and high temperature of the escaping steam, considerable evidence was at hand to show that the activity of the lower or northern part of the Valley had appreciably waned in the course of one year.[2] This was shown by the lower temperatures found in 1919 as compared with the temperatures obtained in 1918 by Sayre and Hagelbarger[3] in the same vents. In the upper or southern end of the Valley a number of fumaroles were discovered in which the temperature of the escaping steam proved to be higher than any so far recorded. Sayre and Hagelbarger unfortunately did not have the opportunity to study these fumaroles in 1918, but several areas were identified in this part of the Valley which they had studied, and even here lower temperatures were found. In 1917 Shipley[4] located a fumarole near the base of Mount Cerberus, in which the temperature of the steam was high enough to cause mercury to boil. In 1919 this same area was carefully examined but no such temperature was found. All of the evidence indicates that in the upper Valley the thermal activity in several areas was lower in 1919 than in 1918 or 1917.

Character of the Eruption as Indicated by Its Effects on Vegetation," *ibid.*, Vol. XIX (1919), pp. 173–209; *The Valley of Ten Thousand Smokes* (Washington: National Geographic Society, 1922), 340 pp., 16 pls., 9 maps. J. D. Sayre and P. R. Hagelbarger, "A Study of Temperatures in the Valley of Ten Thousand Smokes," *Ohio Jour. Sci.*, Vol. XIX (1919), pp. 249–78. J. W. Shipley, "Some Chemical Observations on the Volcanic Emanations and Incrustations in the Valley of Ten Thousand Smokes, Katmai, Alaska," *Amer. Jour. Sci.*, Vol. L (1920), pp. 141–53. C. N. Fenner, "The Katmai Region, Alaska, and the Great Eruption of 1912," *Journal of Geology*, Vol. XXVIII (1920), pp. 569–606; "The Origin and Mode of Emplacement of the Great Tuff Deposit in the Valley of Ten Thousand Smokes," National Geographic Society, *Contributed Technical Papers*, Katmai Series, No. 1, 1923. E. T. Allen and E. G. Zies, "A Chemical Study of the Fumaroles of the Katmai Region," *ibid.*, No. 2, 1923.

[1] *Op. cit.*

[2] Allen and Zies, *op. cit.*, p. 106.

[3] *Op. cit.*

[4] Private communication.

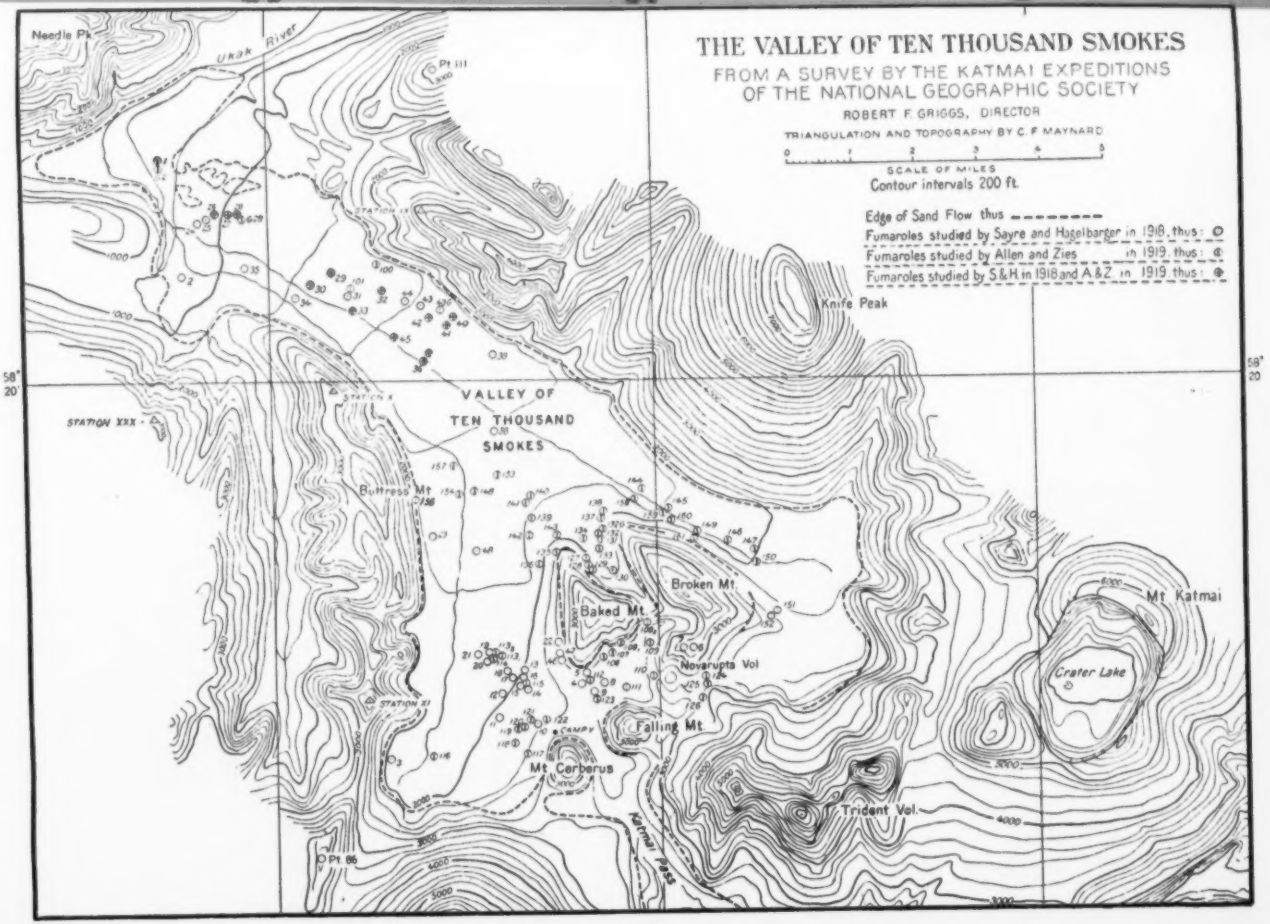
THE VALLEY OF TEN THOUSAND SMOKES
FROM A SURVEY BY THE KATMAI EXPEDITIONS
OF THE NATIONAL GEOGRAPHIC SOCIETY
ROBERT F. GRIGGS, DIRECTOR
TRIANGULATION AND TOPOGRAPHY BY C. F. MAYNARD
SCALE OF MILES
Contour intervals 200 ft.
Edge of Sand Flow thus
Fumaroles studied by Sayre and Hagelbarger in 1918, thus:
Fumaroles studied by Allen and Zies in 1919, thus:
Fumaroles studied by S.&H. in 1918 and A.&Z. in 1919, thus:
Needle Pk.
Ukak River
Pt 111
Knife Peak
VALLEY OF TEN THOUSAND SMOKES
STATION XXX
Buttress Mt
Broken Mt.
Baked Mt.
Novarupta Vol
Falling Mt.
Mt Cerberus
Trident Vol.
Mt Katmai
Crater Lake
Katmai Pass
Pt 86
58° 20'

FIG. 1

The incrustations found at the fumaroles also furnish a clue which frequently helps the observer to ascertain the present and former temperature. When the temperature of the steam was 300° or more, the vents of the fumaroles were usually lined with a hard white baked crust made up of cemented pumice grains. In other cases the presence of pumice cemented with hematite was an indication of elevated temperatures. The presence of large amounts of magnetite was a sure sign of a similar thermal condition. Allen and Zies[1] have shown that relatively large amounts of HCl and HF escape with the steam. It is evident that under these conditions magnetite can not persist for more than a short period when once the temperature of the steam has fallen low enough to permit copious condensation in the throat of the vent. Such fumaroles in which temperatures below 150° were found often retained vestiges of the products mentioned above together with the products characteristic of lower temperatures, namely, sulfur and the chlorides and fluorides of iron and other bases.

In 1919, along with the many active events, there were several hundred fumaroles in the Valley in some of which visible activity had ceased, while in others no thermal activity whatsoever could be ascertained. Usually, remnants of the incrustations characteristic of more elevated temperatures were found.

Finally, in 1919, a few hot springs were found in the lower part of the Valley. This was the first time that such activity had been observed since this region had been under investigation. Hot springs represent the closing stage of thermal activity in a volcanic region.

Evidence was obtained in 1919 by Allen and Zies which points clearly to the most active agency that is responsible for the thermal retrogression just outlined. Before examining this evidence, it will be desirable to present briefly some of the salient features of the pumiceous deposit in which nearly all of the fumaroles are located. Fenner[2] has come to the conclusion that an acid magma was injected as a sill under the old valley floor and in part ejected as a rhyolitic pumice through the fractured floor, completely covering

[1] *Op. cit.*, p. 138.

[2] *Op. cit.*

it to an unknown depth. Griggs,[1] Fenner,[2] and Allen and Zies[3] are in agreement as to the belief that the fumaroles are deep seated in their origin. Lacroix[4] has shown that at Mont Pelée such fumaroles as had their origin in the pumiceous deposit remained active only a few days. In the Valley vigorous activity persisted in 1919, seven years after the great eruption.

The length of time over which the solfatara condition may persist will depend on the rate at which the lava body beneath the old valley floor gives up its heat to the pumice and the steam and other gases escaping from the fumaroles. This rate will be greatly accelerated if drainage water can percolate through the highly porous pumiceous deposit. The solfatara region of Krisuvig, Iceland, is of considerable interest in this connection. Schneider[5] was able to demonstrate the intimate connection existing here between the intensity of the thermal activity and the drainage water. When the solfataras were artificially stopped up, the boiling springs and mud volcanoes rapidly increased in activity. When the surface waters in the vicinity were artificially dammed up, the boiling springs gave off steam instead of water. Allen and Zies[6] have shown that the streams draining the Valley possess several unusual characteristics. In 1919, all of the streams had a much greater volume in the upper part of their course than in the lower part. Knife Creek was fed by a mountain torrent whose volume could be readily estimated. It was found to be 7 feet deep, 5 feet wide, and flowing at the rate of 12 miles per hour. This stream at its confluence with the Lethe, 12 miles down the Valley, had dwindled into an insignificant trickle. The tributaries to the two principal streams behave in a similar manner. The great decrease in volume of Knife Creek and its branches is not due to evaporation, since

[1] R. F. Griggs, *Ohio Jour. Sci.*, Vol. XIX (1918), p. 97.

[2] C. N. Fenner, "The Origin and Mode of Emplacement of the Great Tuff Deposit in the Valley of Ten Thousand Smokes," *National Geographic Society, Contributed Technical Papers*, Katmai Series, No. 1, 1923.

[3] *Op. cit.*, p. 95.

[4] A. Lacroix, *La Montagne Pelée et ses Eruptions*. Paris, 1904.

[5] K. Schneider, "Beiträge zur physikalischen Geographie von Island," *Petermanns geogr. Mitt.*, 1907, pp. 177–88.

[6] *Op. cit.*, p. 117.

the temperature of the water is practically the same in the upper and lower parts of its course. The Lethe is fed by waters derived from the melting of Mageik glacier. About one mile below its source its volume was estimated from the following data: depth, 2 feet; width, 50 feet; rate of flow, 6 miles per hour; and volume about 3,200,000 cubic feet per hour. At its confluence with Knife Creek it had dwindled, in 1919, to a stream 1.5 feet deep, 5 feet wide, and flowing at the rate of 5 miles per hour; volume about 200,000 cubic feet per hour. The Lethe at this point was hot, about 80° C, hence the loss in volume can in part be accounted for by evaporation. This can, however, be only one of the minor contributing causes, since it is only in the lower third of its course that the water becomes appreciably warmer than in the upper part of its course. On the basis of this evidence, and in view of the highly porous character of the pumiceous deposit, Allen and Zies have come to the conclusion that the drainage of the mountain slopes bordering on the Valley is for the most part absorbed by the pumice, vaporized, and drawn into the more or less pervious walls of the fumarole vents by the jet action of the steam and gases escaping from the lava below.

With such an agency at work it is evident that it will take but a few years to bring about an even greater decline in fumarolic activity and an appreciable increase in hot-spring activity. That such a change is likely to take place becomes even more apparent when we bear in mind the relatively rapid lowering of the temperatures of the fumaroles in the lower Valley.

Some idea of the magnitude of this hot-spring activity could be obtained if the amount of water given off as steam by the fumaroles were known. Unfortunately, the available data are insufficient to enable one to obtain with reasonable accuracy the amount of this water. Such meager data as are available will now be used in determining the upper and lower limits of the volume of this water.

In order to obtain samples of the "insoluble" gases, Allen and Zies[1] aspirated the fumarolic exhalations through a copper tube with a cross-section of 50 sq. mm. and condensed the steam in an appropriate chamber. Usually only enough difference in pressure

[1] Allen and Zies, *op. cit.*, p. 113.

was required to overcome the friction offered by the 6-meter tube. The average amount of water condensed at 25° was 350 cc. per 45 minutes, or 470 cc. per hour, per 50 sq. mm. cross-section.[1] This average, in all probability, is much too low since there were a fairly large number of huge fumaroles in which the velocity of the steam and the general thermal activity was so great that no gas samples could be taken. A rough calculation of the cross-section of the steaming vents of the fumarolic areas studied yields the total of 600 square meters. This amount must be much too low since the steaming mud-field areas and many fumaroles on Mount Trident are not included. These data yield the result that about 5,700 cubic meters of water per hour are exhaled by the fumaroles as steam. This volume is equivalent to the volume of a stream 1 foot deep, 10 feet wide, and flowing at the rate of 4 miles per hour.

The value for the upper limit of the volume of water given off as steam is obtained by comparing this volcanic area with that of the well-known area of Larderello in Tuscany. At Larderello the steam is used to generate power, and the amount of water equivalent to the steam exhaled is well known.[2] One of the steam wells, about 20 cm. in diameter, yields 5,500 cubic meters of steam, equivalent to 8 kilograms of water, per second. The characteristics of these steam wells, as deduced from the accurate descriptions given in the papers previously cited, leave the writer with the very definite impression that there are many vents in the Valley in which the volume of steam given off will, when condensed, equal or more than equal this volume of water. The area designated on the map as 32 gave off a column of steam in 1919 that was about 100 feet in diameter. On calm days this column rose to an estimated height of 2,000 feet. Area 101 is located on three parallel fissures about 800 feet long. The average width of the steam cracks was 2 inches, and the steam rose to a height of 30 feet. Either one of these areas must have yielded a very much greater volume than the Larderello steam well. I feel certain that there were in 1919 about

[1] Allen and Zies, *op. cit.*, p. 114.

[2] R. Nasini, *I Suffioni Boraciferi e la Industrie dell' Acido Borico in Toscana.* Rome, 1906. pp. 109. V. Funaioli, "The Larderello Natural Steam Power Plant," *Engineering* (London), 1918.

200 areas in the Valley in each of which the volume of steam was about ten times that of the Larderello well. Using the figure 80 kilograms of water per area, we find that the combined areas would yield 16,000 kilograms of water per second or 58,000,000 kilograms per hour, approximately 58,000 cubic meters per hour. This is equivalent to the volume of a stream 1 foot deep and 130 feet wide, flowing at the rate of 3 miles per hour. This upper limit is in all probability much nearer the truth than the lower limit previously given.

That such a thermal retrogression as outlined in this paper is very likely to take place in the Valley of Ten Thousand Smokes receives considerable confirmation from another source. One of the largest thermal regions in the world is located on the North Island of New Zealand. In 1886 Mount Tarawera, which up to that time was looked upon as an extinct volcano, suddenly became violently active. The explosion blew out enough material to leave a rift in the mountain $\frac{1}{4}$ mile wide and 12 miles long. Many fumaroles were located in this rift. Intense solfataric activity continued for several years and thereupon resolved itself into a series of hot springs and a few steam jets.

It is evident that at some time in the near future the present thermal activity of the Valley of Ten Thousand Smokes will resolve itself into that of a hot-spring area. Considerable interest is thus attached to the changes that will take place in the progression from an intensely hot fumarolic area to that condition in which hot springs are the dominant thermal activity. Equally as interesting, on account of the many economic minerals found in the incrustations, are the mineralogical changes which must of necessity take place as the temperature of the region grows less. For this reason alone the Valley is worthy of additional study.

THE BLACK SHALE OF SOUTHWESTERN VIRGINIA

GEORGE W. STOSE[1]
U.S. Geological Survey, Washington, D.C.

ABSTRACT

Conclusions as to the age and correlation of the black shale in several sections measured in southwestern Virginia are presented by the writer. There are recognized in this area the Genesee shale, Portage shale, and Chemung formation, of Devonian age, and a black shale correlated with the Chattanooga shale but here called the Big Stone Gap shale, of Devonian or Mississippian age, which is overlain by beds of Cuyahoga (Mississippian) age.

In the survey of the pre-Pennsylvanian rocks of Wise County for the Virginia Geological Survey, the writer found it necessary to consider the Black Shale problem. The black shale in this region was formerly mapped by M. R. Campbell[2] as the Chattanooga shale and was regarded by him as of Devonian age. E. O. Ulrich considers that only a small part of the black shale at Big Stone Gap, in Wise County, is equivalent to the Chattanooga, and he is convinced that the typical Chattanooga shale is of Carboniferous age, not Devonian.[3] From the evidence of fossil content, lithologic characters, and sequence of beds Ulrich concludes[4] that the black shale comprising the upper 120 feet of his measured section at Big Stone Gap is Sunbury; 30 feet of underlying reddish shale may be Bedford; 170 feet of dark shale containing linguloids, discinoids, a few conodonts, plant remains, and fish scales and spines are of Cleveland and Huron age; 285 to 485± feet of black and drab shales containing numerous *Sporangites* and conodonts, in the lower part of this section, are Portage; and the basal 170 feet of black shale is Genesee.

The writer in an endeavor to form an opinion of his own as to the relation of these shale formations to fossiliferous Devonian

[1] Published with the permission of the Director, *U.S. Geol. Survey*, and Director, *Virginia Geol. Survey*.

[2] Estillville folio, *U.S. Geol. Survey*, 1894.

[3] *Amer. Jour. Sci.*, Vol. XXXIV (1912), pp. 157–83.

[4] Personal communication.

beds in the vicinity of Saltville, Virginia, which he had previously studied and mapped, made a reconnaissance of the black shale exposures between Saltville and Big Stone Gap, and measured several sections where these rocks were best exposed. The results of this study, which are given in detail in the Wise County report of the Virginia Geological Survey now in press, may be summarized as follows:

The black shale is exposed in two narrow southwestward-trending belts, as shown in the accompanying sketch map of southwestern Virginia (Fig. 1), the eastern belt passing through Saltville and Moccasin Gap, the western one through Clinchfield, Duffield, and Big Stone Gap. The Genesee shale is recognized in all sections in both belts, and its top is taken as the base line in the accompanying chart. It is from 160 to 200 feet thick, and contains abundant *Schizobolus truncatus* in all the sections and, in places, other minute forms common in the Genesee shale of New York. Overlying the Genesee in all sections are interbedded olive to drab and black shales, which range from 400 to 700 feet in thickness. In most sections only conodonts, spore cases of plants, and small fragments of fish and plant remains were found in these beds, but in the Saltville region other fossils, including large, thin-shelled *Goniatites*, comprising the *Manticoceras* fauna of Portage age in New York, were sparingly found. The conodonts found in all the sections are, according to Ulrich, of distinctive type that occur only in rocks of Portage age, and which have been described and figured in reports on these rocks in New York. It seems reasonable, therefore, to conclude that the interbedded olive, drab, and black shales in all of the sections form a unit and are of Portage age.

The Chemung formation, which overlies the Portage in New York, maintains its characteristic lithology and contains its distinctive fossils from its type locality in New York to Saltville, Virginia, where the formation is 1,800 feet thick. It extends but little farther southwestward, however, for only a few hundred feet of these rocks were seen in the section at Holston, and none at all occurs at Mendota. Fossils found in these rocks at Mendota, which in the Bristol folio of the geologic atlas of the United States were reported to be of Chemung age, have since been assigned to the

Cuyahoga formation and are of Mississippian age. The Chemung thins also northwestward and is not present at Clinchfield and Dump Creek nor southwestward in the western belt of shales.

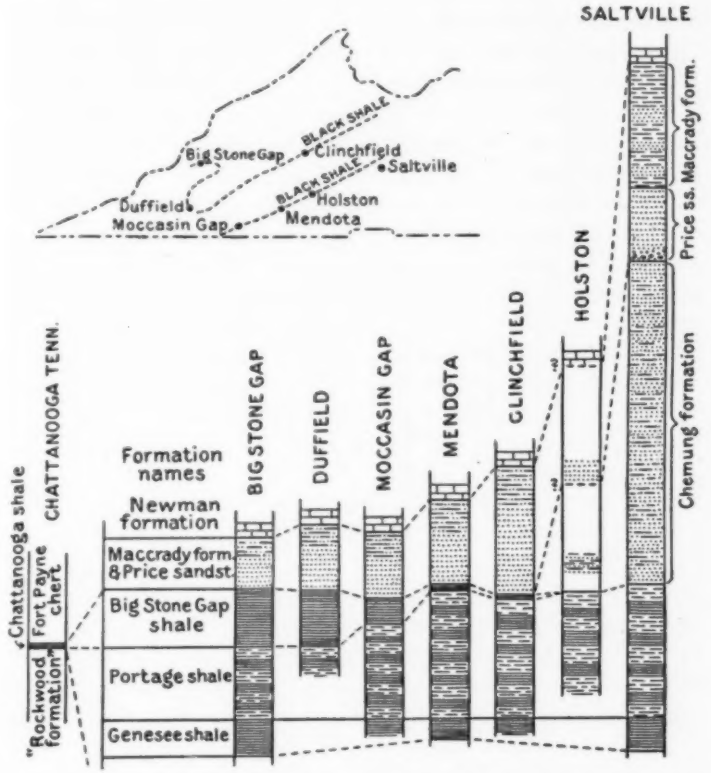

FIG. 1.—Chart of measured sections of the black shale formations of southwestern Virginia, showing correlations by the writer. Location of sections indicated on the accompanying index map of southwest Virginia.

Overlying the Portage shale at Mendota and southwestward in the eastern belt and throughout the western belt is a black shale and dense argillite, which is 320 feet thick in the Big Stone Gap region and 355 feet thick at Duffield. It thins northeastward to 40 feet

at Mendota, to 17 feet at Clinchfield, and, according to Ulrich, to 4 feet northeast of Dump Creek. None is present in the vicinity of Saltville. The distinctive lithologic character of this black shale as well as its scant, minute, but characteristic fauna makes it clearly recognizable in all sections from Big Stone Gap to Clinchfield. Everywhere it is overlain by rocks that contain an abundant fauna which is correlated with the Cuyahoga shale of Ohio. It was not found in any section where Chemung rocks are recognized, so that its relation to the Chemung is not positively established. However, as it lies between the Portage shale and rocks of Cuyahoga age in all the sections referred to, and as there is no similar formation elsewhere between the Portage and the Chemung with which it can be favorably compared, whereas there are reported[1] closely similar black shales just beneath the Cuyahoga shale in Ohio, it is concluded that the correlation of this black shale with the black shales of Ohio, which are called the Sunbury, Cleveland, and Huron, is strongly suggested on purely lithologic and stratigraphic evidence. The few fossils obtained from these black shales in southwestern Virginia also confirm this correlation. In the upper part of the black shale are found a *Lingula* identified by Ulrich as *L. melia*, a form which is reported to occur in the Sunbury shale of Ohio, and conodonts which Ulrich finds differ from those in the Portage shale of New York and resemble those from the Cleveland and higher shales in Ohio. In the lower part of these black shales are found shells identified by Ulrich as *Barroisella* sp., and *Orbiculoidea herzeri*, conodonts, and fish and plant remains, which are the same as, or compare closely with, fossils reported from the Cleveland and Huron shales of Ohio.

In the vicinity of Chattanooga, Tennessee, there is from 10 to 25 feet of black shale and platy argillite called the Chattanooga shale, which in the writer's opinion has the same lithologic character as the black shale here described and which contains similar conodonts, spore cases, and *Lingula melia*. It does not contain *Schizobolus* or other fossils characteristic of the Genesee or Portage, nor does it have interbedded drab or olive shales like those in the Portage. It underlies the Fort Payne chert, which is correlated with the

[1] The writer has no personal knowledge of the Ohio section.

Keokuk formation of the Mississippi Valley, and it rests unconformably on the early Silurian Rockwood formation. The upper black shale in the Big Stone Gap area, therefore, corresponds very closely with the typical Chattanooga shale, and they are believed by the writer to be equivalent, but as Chattanooga has been widely used in a broader sense to include some or all of the underlying dark shale, the name "Big Stone Gap shale" has been adopted for this upper black shale.

Whether the Big Stone Gap shale is Devonian or Carboniferous is not established by the evidence at hand. The Sunbury shale is undoubtedly Mississippian. The Cleveland and Huron shales are classed as Mississippian by Ulrich and others, but are regarded by some as Devonian. Mr. Ulrich lays great stress in claiming its Mississippian age on the widespread diastrophic movement represented by the marked uncomformity at the base of the Chattanooga shale throughout most of Tennessee and Kentucky, and in other parts of the Mississippi Valley, and this argument carries the same weight for the age of the Big Stone Gap shale which is correlated with it.

CORRELATION OF HURONIAN AND GRENVILLE ROCKS[1]

TERENCE T. QUIRKE
University of Illinois, Urbana, Ill.

ABSTRACT

The discovery last summer (1923) that the "Laurentian" complex, between the Huronian area and the Bancroft-Haliburton area, contains Huronian sediments metamorphosed into rocks of Grenville type, and that with these paragneisses there are amphibolites due to the metamorphism of Keweenawan diabase, indicates that the Grenville rocks of Southeast Ontario should be correlated with the Huronian sediments, and that the batholiths which intrude the Grenville schists and gneisses are post-Huronian in age rather than pre-Huronian and should be mapped as of Keweenawan age rather than Laurentian.

INTRODUCTION

In North America a series of areas underlain by pre-Cambrian rocks extends from the Lake of the Woods 1,000 miles to the Atlantic Coast. Unhappily, this great zone is not without serious gaps, across which correlation is discouragingly difficult. These gaps separate five distinct areas, the north-shore region of Lake Superior, the south-shore region of Lake Superior, the Temiskaming area north of Lake Huron, the Laurentian area, and the Appalachian district. With the exception of local difficulties and details, the north- and south-shore divisions of Lake Superior are satisfactorily correlated, and geologists will welcome a definite correlation by Collins[2] of the Bruce and Espanola limestones of the north shore of Lake Huron with the Kona dolomite of the Lake Superior areas. These three western areas provide correlation between the representatives of the Huronian series, and by means of the persistence of the Keweenawan diabase, the pre-Huronian granite, and the Keewatin volcanic schists; there are also well recognized structural connections and aids to correlation.[3] But from Minnesota to

[1] Published with the permission of the director of the Geological Survey of Canada.

[2] W. H. Collins, *Geol. Surv. Can.* (memoir in preparation).

[3] For instance, the correlation of the Virginia and Tylor Slates as being opposite sides of a syncline. A. C. Lane, *Amer. Jour. Sci.*, Vol. XLIII (1917), p. 44. See also C. K. Leith, *Econ. Geol.*, Vol. XVIII (1923), pp. 288–90.

New York there is only one sedimentary series more than local in distribution which may furnish a stratigraphical basis for correlation; that is the Huronian. Where that is present, correlations have been made; where it appears to be absent, progress of this kind has stopped. There are problems serious enough and difficult enough within each of the eastern areas which probably hinder the correlation of the rocks within the two, but the areas are separated more by geographical than by geological barriers, and their correlation seems certain of ultimate success as time and work go on. However, between the Laurentian areas which contain recognizable units for correlation, particularly the Grenville series, and the Huronian areas, there is a zone of granite gneisses 100 miles wide. This appears to be the hardest gap to bridge. The outstanding problem in pre-Cambrian correlation seems to be the relation between the Huronian series of the three western areas and the Grenville of the two eastern areas.

The recent work by Collins, however, in the areas studied by Bell and Barlow, indicated that it might be possible to find a means of carrying a correlation across this complex from the Huronian rocks on the west to the Grenville on the east. Although field work has so far been done on this problem for only one season, there are indications that it will become entirely successful with a definite conclusion, predicted by Lane[1] some years ago, that the Huronian and the Grenville rocks, being mutually exclusive, are identical (Fig. 1).

No one is willing to conclude that all the sedimentary remnants in the Laurentian and Appalachian areas are of one age, but provided a correlation of one stratigraphical member in these areas can be made with one in the Huronain area, a basis for correlation of other formations becomes possible by means of the age of widespread granite intrusions and periods of profound erosion, as far as these may be recognized. If one were able to correlate with confidence even igneous intrusions on both sides of this gap, a great deal would be gained, but unhappily hitherto no such conclusion has been possible. It has been assumed that the granite intrusions cutting the Grenville formations are equivalent in age to the granite which

[1] A. C. Lane, *Amer. Jour. of Sci.*, Vol. XLIII (1917), p. 44.

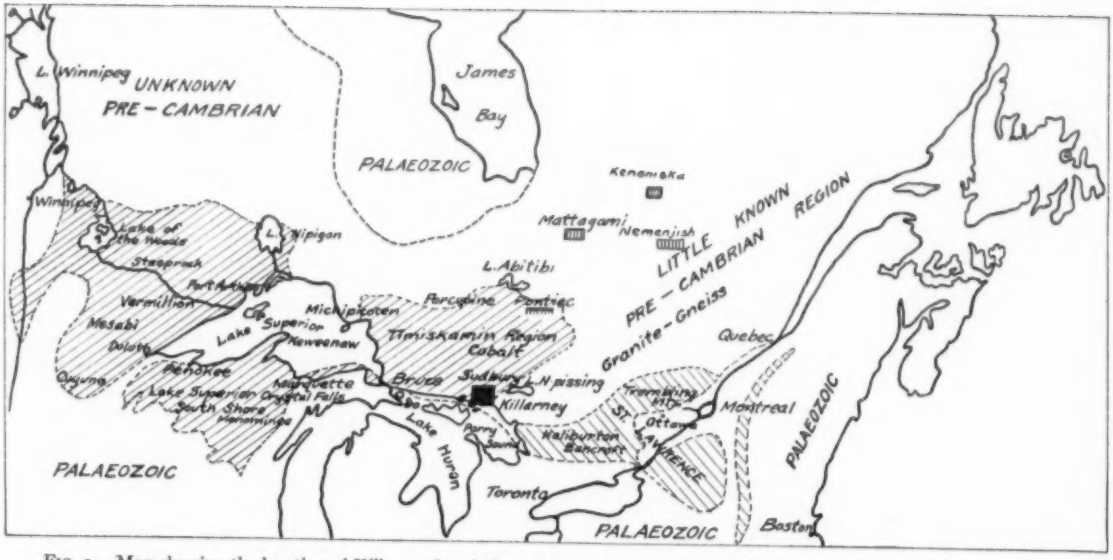

FIG. 1.—Map showing the location of Killarney in relation to the main pre-Cambrian districts of northeastern North America

intrudes the Keewatin and which lies unconformable beneath the Huronian rocks, but that correlation is based on a generally recognized assumption and not on any sort of demonstration.

Nevertheless, it is on this basis that the granite referred to in the three western districts has come to be called Laurentian and also so established by the International Committee on Nomenclature in 1904.[1] The general recognition[2] of granites of more than one age in the western areas discredits the conclusion that only the oldest of these granites is comparable in age to that in the Laurentian area. It thus becomes necessary to determine whether the granite batholiths of the Laurentian area are to be compared with the oldest or with a younger known granite of the western areas.

In the western areas, there is a widespread distribution of dike rocks and effusives of Keweenawan age. In the eastern areas these are apparently lacking. Thus, a third means of correlation, applicable in western areas, seems to fail at the eastern gap.

The structure of the western areas, largely by means of the stratigraphical members, has been worked out in such detail that the correctness of the general geology and its correlation have been proved over and over again. In the eastern areas the widespread invasion of batholithic masses and a general tendency on the part of the workers to distrust structural methods under such conditions have worked against any notable advances along this line of attack.

Thus, across this gap, we lack correlations used successfully in western areas as follows:

1. The Huronian sedimentary series.

2. The granites older (Laurentian) and younger (Algoman? and Killarnean).

[1] International Committee on Geological Nomenclature, *Jour. of Geol.*, Vol. XIII (1905).

[2] Sir William Logan, *Geol. Surv. Can.* (1863), p. 55; International Committee on Geological Nomenclature, *Jour. of Geol.*, Vol. XIII (1905), pp. 94 and 103; C. W. Van Hise and C. K. Leith, *U.S. Geol. Surv. Bull. 360* (1909), p. 28; A. P. Coleman, *British Assoc. Adv. Sci.* (1910), quoted by Lawson, *op. cit.*, p. 106; A. C. Lawson, *Geol. Surv. Can., Mem. No. 40* (1913), p. 107; W. G. Miller and C. W. Knight, *Ontario Bur. Mines*, Pt. II (1914), pp. 127–29; R. C. Allen and L. P. Barrett, *Jour. of Geol.*, Vol. XXIII (1915); A. C. Lane, *Amer. Jour. of Sci.*, Vol. XLIII (1917), 43 and 44; W. H. Collins, *Geol. Surv. Can., Mus. Bull. No. 22* (1917).

3. The Keweenawan diabases and lava flows.

4. Persistence of great structural features.

These desirable correlations depend uniformly upon a successful tracing of the Huronian sediments. The recognition and relations of these sediments are the only means of identifying the granites of different ages; of separating the Keweenawan diabases and their metamorphic equivalents from similar rocks of greater age, particularly Keewatin rocks; and of working out the structure of the gneissic and granite complex, for we can determine the structure of such an area only when we can identify and recognize definitely zones of paragneisses.

There is nothing in the Temiskaming area, except what is demonstrably of Huronian age, metamorphosed by younger granite, which appears to correspond to the Grenville series.[1] We must, therefore, look in the Grenville and Laurentian areas for the equivalents of the Huronian rocks. The logical line of attack is the study of the zone of contact between the Huronian area and the Laurentian area along the line which extends from Killarney to Lake Temiskaming. If the Huronian rocks cannot be traced into the areas of igneous gneisses which border them on the east (so far as ordinary stratigraphical methods are concerned), all hope of correlation in this direction must be abandoned.

The facts.—The Huronian rocks at Killarney are cut off transverse to the strike by granite and granite gneisses. The granite is younger than the Huronian sediments which it invades and transgresses, and it is younger than the paragneisses which border it on the east. More specifically, the granite is older than the dykes of olivine diabase and younger than the dykes and masses of ordinary quartz diabase, which are ordinarily said to be of Keweenawan age. It is very much younger than the Laurentian granite which lies unconformable beneath the basal conglomerate of the Huronian series. The continuation of gneisses and granite of this type have been mapped by other workers as Grenville and Laurentian gneisses.

[1] If we except the Temiskaming rocks of Miller and Knight, which are limited as far as known to a small area on Lake Temiskaming, and whose relations to the Bruce series are unknown, and if we except the strip of sediments between Sudbury and Algoma, called the "Sudbury Series" by Coleman.

The problems.—What has become of the many cubic miles of Huronian sediments, largely indigestible quartzites, which seem to have been swallowed up by the granite and gneiss? Is this granite the same as that which is usually mapped as Laurentian east of Killarney? If so, what is the relation of the Huronian sediments to the Grenville sedimentary schists and gneisses, which are also older than the invading (Laurentian?) granite?

The conclusions.—The Huronian sediments are intruded and metamorphosed by granite into paragneisses of igneous aspects, in many places not to be distinguished from rocks of igneous origin. The inclusion of Huronian sediments, in less severely altered condition of metamorphism, has provided the stuff out of which have been made rocks of Grenville type. Rocks of the same type make up the terrane between Killarney and the Bancroft-Haliburton area, and we must be prepared to find that some, at least, of the Grenville of the Haliburton area are of Huronian age, and that some of the intrusive granites, mapped and described as Laurentian, are really younger than the Huronian rocks. Thus, it is necessary critically to distinguish between granitic rocks of pre-Huronian and granitic rocks of post-Huronian age. Among American geologists it is probable that the more acceptable practice would be to call the older of the two the Laurentian granite and to apply the newer name, Killarney granite, to the younger of the two, even in cases where the younger may have been named Laurentian for a very long time.

The discovery that the Huronian rocks are metamorphosed into rocks which are of the same character as the Grenville gneisses, and which can be traced in a fragmentary way from Killarney to Haliburton, indicates that the Grenville rocks are the Huronian sediments, and the post-Grenville granites are not to be correlated with the Laurentian granites of Lakes Superior and Huron, but with the Killarney and other Keweenawan granites.[1]

Previous workers.—In spite of the present relative inaccessibility of the Killarney area, it has long been known to geologists. Indeed,

[1] This practice would be in accord with the recommendations of the International Committee as to the meaning of the term Laurentian in reference at least to the Huronian formations. *Journal of Geology*, Vol. XIII (1905), pp. 89–104.

it seems scarcely possible that the earliest travelers would not make note of the remarkable physiographic features of the district, and it is less probable that geologists would fail to give it special study.

Long before the white man came, the village of Killarney was in existence, being located on the narrow sheltered inlet which gave the place its Indian name of Shebahanahning (the place of the clear passage).[1] Confusion will be avoided if readers will bear in mind that only the older names are used in the reports prior to 1877. The older name is not spelled consistently, in the French works being written, "Chebaouenahning." In any case, there can be no doubt as to the place referred to because of its remarkable geographic position on an inlet and at the edge of the granite and the sediments.

In his report on the French River sheet, Bell states that the area was visited by Murray in 1847, '55, '56, and '57, and by Bell[2] in 1859, '65, '76, '86, '91, and '92. In the year 1891 besides his regular assistant, A. E. Barlow, Bell had with him Messrs. W. G. Miller and R. W. Brock, among others, and in 1892 he had Messrs. Miller[3] and Brock[4] again. Coleman[5] appears to have visited the region some time previous to 1914, and Collins'[6] surveys brought him there in 1916. Of the seven men listed, four are still able, fortunately, to bear witness as to the matters advanced in this paper. Although Murray, Bell, and Barlow have been for several years deceased, we have excellent records of their discoveries and opinions in their reports.

IDENTITY OF HURONIAN ROCKS

The first question is as to the age of the sedimentary formations. Murray[7] called the sedimentary rocks Huronian. Bell[8] did the

[1] R. Bell, *Geol. Surv. of Can., Reports, 1876–77*, p. 209.

[2] R. Bell, *Geol. Surv. of Can., Ann. Report*, Vol. IX (1898), Pt. I, p. 6.

[3] Provincial Geologist of Ontario, 1902—.

[4] Director, Geological Survey of Canada, 1908–14; Dean, Faculty Applied Science, University of British Columbia, 1914—.

[5] A. P. Coleman, *Ontario Bur. Mines*, Vol. XXIII (1914), pp. 222–24.

[6] W. H. Collins, *Geol. Surv. Can., Mus. Bull. No. 22* (1916).

[7] Alexander Murray, *Geol. Surv. of Can., Reports, 1856*, p. 168.

[8] R. Bell, *Geol. Surv. of Can., Reports, 1876–77*, pp. 208–09.

same, so did Barlow.[1] In this connection it is proper to recall that these men were inclined to include with the Huronian sediments certain of the Keewatin stratiform schists. Careful study of Murray's work, however, leaves little doubt that he meant the sediments at Killarney to be considered of the same age as those near Thessalon. The reference to the work of Barlow makes it quite clear that in the case in point he deliberately correlated the sediments at Killarney with those near Bruce mines and Thessalon, which are part of the original Huronian in the strictest sense of the term. It is probably true that the practice and intentions of Bell were more questionable than those of either Murray or Barlow in regard to the use of the term Huronian.

Coleman[2] definitely stated that the rocks at Killarney are of Sudbury age, and thus older than the Huronian, and thereby explained the apparent confusion of earlier workers. In this correlation he was under the great handicap of lack of consecutive areal mapping from either the Sudbury region or the original Huronian area. With the enormous advantages of extensive areal mapping, Collins[3] was able definitely to place each formation in the complicated structural relations found in the MacGregor Bay anticline and at Killarney as the equivalent of the formations in the original Huronian area, thus settling, it would seem absolutely, the age of the sedimentary rocks at Killarney (Fig. 2); they are of Huronian age.

During the past summer there has been discovered on Tyson Lake, several miles within the granitic area, and separated from the Huronian formations by intervening intrusive granite and gneiss, a series of contact metamorphosed sediments which are correlated with the Huronian rocks described and identified by Collins near Killarney and about the eastern end of Lake Panache (Fig. 3). Precisely the same arguments which[4] Collins used to establish the

[1] A. E. Barlow. "Relations of the Laurentian and Huronian Rocks North of Lake Huron," *Bull. Geol. Soc. Am.*, Vol. IV (1893), pp. 313–32.

[2] A. P. Coleman, *Ontario Bur. Mines*, Vol. XXIII (1914), pp. 222–23. Cf. C. W. Knight, *Ontario Bur. Mines*, Vol. XXIV (1915), pp. 228–29.

[3] W. H. Collins, *Geol. Surv. Can., Mus. Bull. No. 22* (1916), pp. 9–10.

[4] *Ibid.* Cf. A. C. Lawson, *Univ. Cal. Publications, Geol.*, Vol. X (1916), p. 4.

identity of the sediments at Killarney apply to the correlation of the metamorphic rocks on Tyson Lake with the Huronian series. The succession is the same as that of the original Huronian rocks, the Bruce series being represented by members which correspond

FIG. 2.—Espanola formation in Killarney Bay, contact metamorphosed into black amphibolite.

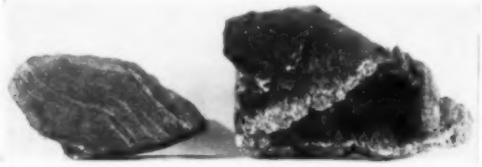

FIG. 3.—Espanola formation collected on Tyson Lake, contact metamorphosed and injected with granite stringers.

in every way with the Mississagi quartzite, the Bruce conglomerate, the Bruce limestone, the Espanola limestone, and the Serpent quartzite. Furthermore, in spite of igneous intrusions and local faulting, the stratigraphic succession of these members is obviously the same as that of the Huronian members with which they are correlated. Stratigraphically above these beds of the Bruce

series lie the Cobalt series, separated from the Bruce series by a zone of igneous metamorphism, but representing, in places which have escaped the more profound type of alteration, specifically on Annimack Lake, the typical phases of the Gowganda formation (Fig. 4). These formations are cut by diabase dykes which are metamorphosed to about the same extent as the sediments, and they are cut by younger olivine diabase dykes which show a much slighter degree of metamorphism. These facts check exactly with those discovered in the regions where the age and identity of the formations have been established by Collins.

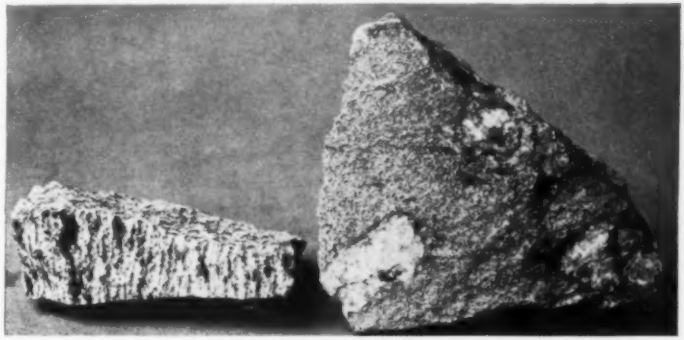

FIG. 4.—Gowganda formation (Cobalt conglomerate) from Annimack Lake, contact metamorphosed by granite.

Similarly, in the Beaverstone Bay locality, a dozen miles within the "Laurentian" area, there is intruded by granite the following series of rocks: a quartz diabase which intrudes a massive highly crystalline quartzite, lying below a conglomerate, which is overlain by a well-bedded amphibolite (Fig. 5) corresponding mineralogically with the contact metamorphic phases of the Espanola formation in Killarney Bay, where it has been identified by Collins. This is the Bruce series: Mississagi quartzite, Bruce conglomerate, and Espanola formation, intruded by Keweenawan diabase. The Beaverstone Bay sedimentary group is cut off on the eastern side by a fault breccia, which separates the rocks of evident sedimentary character from a series of migmatitic gneisses of questionable

origin. No authorities can be called on in this connection, because none of the earlier workers seem to have seen the rocks mentioned, or if they did see them they did not recognize what they were, and none of the later geologists seem to have visited the localities described, several miles back from the line of major contact.

In addition to the field work of the writer, the authorities cited show that no doubt can attach to the proposition that the rocks which border the Killarney granite on the west are of Huronian age.

FIG. 5.—Espanola formation in Beaverstone Bay, contact metamorphosed into black amphobolite.

CONTACT OF GRANITE AND HURONIAN ROCKS

The next point to examine is the nature of the contact between the Huronian sediments and the granite at Killarney. Murray[1] says that although the rocks between Lake Nipissing and Georgian Bay are Laurentian and Huronian, he did not see the actual contact anywhere; consequently, from this report it is clear that he had no evidence or opinions upon the matter. However, in his report of the next year,[2] he noted on the shore line between Killarney and the mouths of French River that the gneiss includes quartzite, contorted and folded into undulations of considerable size, causing frequent

[1] Alexander Murray, *Geol. Surv. Can., Reports, 1856*, p. 168.

[2] *Geol. Surv. Can., Report of Progress* (1857).

repetitions of bands. He does not state what age he considered these sediments to represent, although he would probably have considered them to be of the same age (Laurentian) as the including gneisses, inasmuch as the intrusive nature of the granites was not at that time recognized, almost thirty years before the work of Lawson[1] on Rainy Lake. Bell[2] states that the granite is apparently intrusive into the quartzite at Killarney, but that the granite is distinct from the gneiss. Barlow,[3] on the other hand, takes the view that the granite and gneiss are of the same age, merely different

FIG. 6.—Gowganda formation intruded by granite dykelets on Kakakise Lake

phases of the same thing, and that both are intrusive into the Huronian formations, for the following reasons:

1. The diverse stratigraphic relations of the two rocks along their line of junction. . . . .

2. The alteration of the sedimentary rocks along the line of junction. . . . .

3. The inclusion of angular fragments in the mass of the gneiss which are clearly referable to the adjacent sedimentary strata.

4. The occurrence of gneissic intrusions as well as more coarsely crystalline apophyses of pegmatite both interlaminated with and transverse to the bedding of the Huronian rocks.

The intrusive character of the granite is agreed to by Coleman[4] and Collins.[5] This point cannot be in doubt (Fig. 6).

[1] A. C. Lawson, *Ann. Report Geol. Surv. Can.*, Pt. F (1887–88).

[2] R. Bell., *Geol. Surv. Can., Ann. Report*, Pt. I, Vol. IX (1898), p. 7, and *American Geologist*, Vol. XI (1893), pp. 135–36.

[3] A. E. Barlow, *Bull. Geol. Soc. America*, Vol. IV (1893), p. 330.

[4] A. P. Coleman, *Ontario Bur. Mines*, Vol. XXIII (1914), p. 214.

[5] W. H. Collins, *Geol. Surv. Can., Mus. Bull. No. 22* (1916), p. 10.

KILLARNEY GRANITE AND THE GNEISS

If it is admitted that the granite is intrusive in the Huronian rocks, evidence is required to show that the gneiss is of the same age as the granite, or that its relations to the Huronian rocks are intrusive. Murray apparently regarded them as of the same age, at least he made no attempt to separate them. Bell seems to have been the first to recognize the granite as such, as mentioned in an earlier part of this report, and he thought that it was younger than the gneisses. In this opinion he was vigorously opposed by Barlow,[1] as quoted above, and as follows:

> The Laurentian to the north of Lake Huron is chiefly represented by gneiss which differs from granite only in being foliated. Frequently the foliation is quite distinct, although sometimes it is obscure and occasionally it cannot be detected at all, the rock then being indistinguishable from ordinary irruptive granite. . . . . Although in many cases there is the clearest evidence that these granites cut the gneiss, yet for the following reasons both may be considered to have had a common genesis.
>
> 1. The presence of streaks and lenticular patches of darker-colored material in the midst of the non-foliated areas, all of which have a more or less constant direction.
>
> 2. The frequent absence of any sharp line of division between the granite and the gneiss, the one passing into the other by insensible gradations.
>
> 3. The occurrence of dykes and veins of pegmatites cutting both and one another clearly belonging to the same period, although the fact of one cutting the other would seem to indicate a lapse of time, which in this case doubtless was of small import.
>
> 4. Their close resemblance in composition, appearance, and behavior. . . . .
>
> These masses of granite may therefore be regarded as non-foliate areas of gneiss, representing simply certain irruptions from the same magma from which the gneiss itself has solidified, and although a sufficient time has elapsed to allow of the more or less complete consolidation of the gneiss, yet they represent the same age in geologic time.

Coleman[2] pointed out that Bell was probably swayed in his judgment as to the age of the Killarney granite by his belief that the Laurentian rocks are older than the Huronian formations; consequently, he would incline to agree with Barlow that the gneiss

[1] *Op. cit.*, p. 315.

[2] *Op. cit.*, p. 223.

and the granite are one in age—Laurentian. As quoted on a previous page, Collins[1] was holding himself open to conviction, but has since expressed his satisfaction with the conclusion that the Killarney granite is of the same age as the gneisses which border it on the east (Fig. 7).

On Tyson Lake, on Beaverstone Bay, and on Annimack Lake it is perfectly clear that the intrusive rocks are gneisses, and that the sedimentary rocks grade imperceptibly into rocks which are highly feldspathic gneisses of igneous aspect. The intrusive relation of the gneisses in regard to the sediments is clear, but the line of division between the granite and the gneisses is everywhere,

FIG. 7.—Killarney layered gneiss on Kinley Lake

where perceptible at all, very gradual. As Barlow said, the intruded gneiss differs from granite only in being foliated.

HURONIAN-GRENVILLE CORRELATION

If now it is admitted that the granite and gneiss are one in age and that both include masses of altered sedimentary rocks, it remains to show reason why these sedimentary schists and gneisses should be correlated with the Grenville series. Murray does not seem to have connected the sedimentary gneisses which he noted with those farther east, although Logan[2] probably would have done so had he realized the amount of sedimentary schists and limestone

[1] Personal communication.

[2] Sir William Logan, *Geol. Surv. Can., Report of Progress* (1863), p. 47.

represented in the Killarney area. He noted particularly that there are no limestones known along the shore between Muskota and Killarney, although there are bands of the garnetiferous schists which usually accompany the limestone at Muskota, and on the basis of this supposed lack he called the rocks Laurentian as far as Killarney.[1] Murray[2] did not call these rocks Grenville (upper Laurentian), even though he knew of the presence of limestone in the gneiss about Lake Nipissing. However, Bell[3] seems to have studied these limestone bands rather carefully, describing four or five associated with conglomerates, varying in width from fifty to one hundred feet, and otherwise seeming to have considerable resemblance to the Bruce conglomerate and limestone of the Huronian series. And in a later report[4] he states definitely that the rocks along the southeast side of the Huronian rock area at Killarney resemble the Grenville series of the lower Ottawa district, and calls them Upper Laurentian (Grenville) with the exception that there are no limestones within the French River sheet, although there are five bands of limestone, as above, like those of the Grenville series in the neighboring Parry Sound area. Evidently bell thought the sedimentary schists were of the same age as the Grenville. Barlow[5] has little interest in this point, believing, as he did, that the Grenville bands were merely igneous phases of the Laurentian gneiss. Coleman[6] helps to bridge the gap by describing several localities of rocks which he calls Grenville, southeast of Sudbury, apparently the continuation, along the strike, of the sedimentary gneisses at Killarney. He notes that the limestone is entirely different from the small bands of limestone found in later formations in the region, which are not crystalline, and is closely like the typical Grenville limestones of southeastern Ontario and Quebec. More

[1] The garnet schists are so abundant in Collins Inlet that the shore is lined in places with purple garnet sand, but Logan did not know this.

[2] Alexander Murray, *Geol. Surv. Can., Report for 1853–54*, p. 185.

[3] R. Bell, *Geol. Surv. Can., Report for 1876–77*, pp. 202–8.

[4] R. Bell, *Geol. Surv. Can., Ann. Report*, Vol. IX (1898), pp. 9–10.

[5] A. E. Barlow, *American Geologist*, Vol. VI (1890), p. 29, and *Bull. Geol. Soc. America*, Vol. IV (1893), p. 330.

[6] A. P. Coleman, *Ontario Bur. Mines.*, Vol. XXIII (1914), pp. 208–11.

recent[1] work has shown that there are many crystalline bands of limestones in the Huronian formations, but that does not make the bands referred to by Coleman any less similar to those at the Grenville localities. Among the Grenville, Coleman included certain sedimentary schists near Wanapitei which were described by Walker.[2] Just as Collins[3] has shown that many of the occurrences, mapped by Coleman and other officers of the Ontario Bureau of Mines as Grenville, are really of Huronian age, so it has been discovered that many gneisses and schists within the Laurentian area near Killarney, which are comparable to the Grenville series, are of Huronian age. It is suggested as a reasonable extension of the information already gained that the limestone bands about Lake Nipissing also are Huronian, as well as those at Parry Sound, thus bringing the extension of Huronian schists very near the Haliburton-Bancroft area. It is a reasonable assumption that all these sedimentary schists and gneisses are of the same general age. Certain it is that where these Grenville rocks are found close enough to the Huronian formations to make their correlation possible, they have been found to be identical.[4]

NAME OF GRANITE

The previous premises being acceptable, what can be said as to the naming of the granites and gneisses? In description they coincide with the gneisses discussed by Logan[5] in 1845, and later named Laurentian. They were called consistently Laurentian by Murray[6] after 1853. In the references quoted and cited previ-

[1] W. H. Collins, *Geol. Surv. Can.* (memoir in preparation); C. W. Knight, *Ont. Bur. Mines, Ann. Report*, Vol. XXIV (1915), Pt. II, p. 241; T. T. Quirke, *Geol. Surv. Can., Mem. No. 102* (1916), p. 35.

[2] T. L. Walker, *Quar. Jour. Geol. Soc. London*, Vol. LIII (1897), p. 42.

[3] W. H. Collins, *Geol. Surv. Can.* (memoir in preparation).

[4] A. C. Lane, *Amer. Jour. Sci.*, Vol. XLIII (1917), p. 44. Lane makes the same correlation on more general principles.

[5] Sir William Logan, *Exploration geologique du Canada, 1845–46*, pp. 43–55; *Part II Exploration geologique du Canada., 1852–53*, p. 8; and *Geol. Surv. Can., Report of Progress* (1863), p. 22.

[6] Alexander Murray, *Geol. Surv. Can., Reports for 1853*, p. 185; *for 1856*, p. 168; *for 1857*, Appendix No. 32.

ously, Barlow, Bell, Coleman, Walker, and Collins referred to the gneiss and granite as Laurentian. This rock series has been called consistently Laurentian, but it is surely younger than the Huronian rocks and should be called post-Huronian and not Laurentian. Miller and Knight[1] have pointed out that from the beginning Logan and Murray recognized that some granites are older than the Huronian rocks, and that some are younger, but they were not able to map them separately in all places, consequently their original name Laurentian was bound to lead to confusion. Algoman[2] is the name proposed and generally accepted for a younger granite. Unluckily, by definition the Algoman granite is older than the Animikie series, being supposed to cut the Huronian series, exclusive of the Cobalt series[3] and to be older than the Keweenawan diabases. With this idea Miller and Knight agreed in 1914,[4] correlating the Sudburian and Temiskamian as being in age between the Laurentian and the Algoman granites, and the Grenville as being pre-Laurentian, not merely pre-Algoman. No such granite as the postulated Algoman has been found in the north-shore region of Lake Huron, and certainly the Killarney granite and gneiss have no such relations. Thus the gneisses between Killarney and Parry Sound cannot be called Laurentian, because they are too young, nor can they be called Algoman, because they are not older than the Cobalt series and the Keweenawan diabases which they intrude. The granites and gneisses which cut Grenville schists are probably, in general, of Killarney age, (Keweenawan), and the Grenville series themselves are probably Huronian, contemporaneous with, and to be correlated with the rocks known on the north shore of Lake Huron.

[1] W. G. Miller and C. W. Knight, *Ontario Bur. Mines*, Pt. II (1914), pp. 127–29. Cf. International Committee on Geological Nomenclature, *Jour. Geol.*, Vol. XIII (1905), p. 103. Also, C. Van Rise and C. K. Leith. *U.S. Geol. Surv. Bull. No. 360* (1909), p. 28.

[2] A. C. Lawson, *International Geol. Congress* (1913), and *Geol. Surv. Can., Mem. No. 40* (1913), pp. 5 and 107–8.

[3] A. C. Lawson, *University of Cal. Pub., Bull. of Dept. of Geol.*, Vol. X (1916), pp. 1–19, and *op. cit.*

[4] A. C. Lawson, *International Geol. Congress* (1913), and *Geol. Surv. Can., Mem. No. 40* (1913).

QUARTZ DIABASE

A further indication as to the age of the Killarney and the so-called Laurentian gneisses to the east is furnished by a consideration of the distribution of the Keweenawan diabase. This series of extrusive and intrusive rocks is well represented everywhere in the pre-Cambrian districts of Lakes Huron and Superior, except in the areas which lie southeast from the line of contact between the so-called Laurentian district and the Huronian areas, the line which runs from Killarney northeastward to Lake Temiskaming. Logan[1] noted that the Huronian rocks are not known to extend farther east than Killarney (Shebahahnahning). However, he made no suggestion as to the cause of this abrupt ending. Adams[2] and Barlow report abundant amphibolites of igneous origin in the Bancroft-Haliburton areas. These they describe as altered dykes, and in some cases as probably diabases.[3] If these altered rocks do not represent the Keweenawan diabases, how can one explain the abrupt cessation of the Keweenawan diabases at the Killarney line? They can be mapped on the west side of the dividing line, they have been traced by the writer into the gneissic area; they are concluded to be represented in the Grenville-Laurentian areas by some of the amphibolites mapped by Adams and Barlow. Inasmuch as the Keweenawan diabases and the amphibolites of igneous origin are mutually exclusive, they are probably identical. This is an argument, although not a proof, that the granites of Killarney age extend into the Grenville areas and have changed the Keweenawan diabases into amphibolite (Fig. 8).

GENERAL STRUCTURE OF GNEISSES

A further argument that the Huronian rocks are identical with those mapped as Grenville, aside from their stratigraphic correlations, already discussed, comes from a consideration of the general structure of the Huronian terrane. If the altered gneisses and schists east of Killarney are not metamorphosed Huronian formations, what

[1] Sir William Logan, *Geol. Surv. Can., Report of Progress* (1863), p. 60.

[2] F. D. Adams and A. E. Barlow, *Geol. Surv. Can., Mem. No. 6* (1910), p. 25; pp. 160–61.

[3] *Ibid.*, pp. 162–63. Cf. A. E. Barlow, *Geol. Surv. Can., Mem. No. 57* (1915), pp. 50, 51, and 55.

has become of that great series of sediments? Faulting is a process of displacement, not of destruction, and in faulted regions of the type exemplified by the folds and faults north of Killarney we look for a continuation of faulting of imbricate character, expressed in repetitions of the stratified rocks. The region has suffered an intense shortening in a northwest-southeast direction, which has folded the Huronian rocks into the region of free folding represented by the LaCloche Mountains. North of the mountains, in the Espanola area particularly, there is a zone of imbricate slice-faulting, causing many repetitions of parts of the southward dipping

FIG. 8.—So-called Laurentian layered gneiss and amphibolite on Grondine Point, Georgian Bay. This exposure is typical of the Huronian and Keweenawan complex near Killarney.

Huronian rocks. South of the mountains the same type of structure persists, in combination with a rupture along the crest lines of anticlines, which has given rise to a series of sliced repetitions, obscured in part by the invasion of granite along the zone of major rupture and by the upfaulting of masses which have suffered the intense contact metamorphism characteristic of those formations affected at great depths. On each flank of the mountains there has been found a series of at least three major thrust faults, which together continue the shortening which has found its most striking relief in the folding of the mountains.

We should not look for this type of structure in a region which is of batholithic character. The structure of the gneissic area appears

to continue the structure of the Huronian terrane; it is remarkable for the persistence of dip and strike as far east as the mouths of the French River, south and east of which the rocks are folded as if they were sedimentary rocks.[1] The gneissic rocks include some which are clearly of sedimentary origin, folded with the gneisses, and indicating that the structure of the gneisses is due to the control of sedimentary series. This is so clear that almost everybody would be willing to concede it. The question remains as to why this control on the basis of structure should be ascribed to Huronian rocks rather than to rocks of some other age. A continuation of the type of structures in the Huronian terrane is quite in harmony with the structure in the gneissic area; consequently, it is reasonable to conclude that the areas are contiguous parts of the same structural member, composed of the same constituents.

SUMMARY AND CONCLUSION

In conclusion it may be stated that over and above the discoveries in the field here reported, authorities indicate that the sediments at the Killarney district are of Huronian age, intruded by granite and gneiss, and that the sedimentary gneisses within the granitic area should be correlated with the "Upper Laurentian," or Grenville series. Much of the "Lower Laurentian" granite of Logan is Keweenawan in age (neither Laurentian nor Algoman) and may be called Killarnean.

Further evidences as to the correctness of the foregoing correlation are afforded by the distribution and relations of the quartz-diabase in reference to granite, and by the general structure of the gneissic area as compared with that of the Huronian terrane.

The vulcanic, stratigraphical, and structural evidences, as far as they are known, indicate that the Grenville series of southeastern Ontario should be correlated with the Huronian series of the north shore of Lake Huron.

[1] Alexander Murray, *Geol. Surv. Can., Report of Progress* (1857). Robert Bell, *ibid.* (1876–77), p. 195; *Amer. Geologist*, Vol. XI (1893), pp. 135–36; *Geol. Surv. Can. Ann. Report*, Vol. IX (1898), Pt. I, p. 10.

"Throughout the whole region lying southeast of the great Huronian belt the gneisses are of the typical upper Laurentian varieties. They are evenly stratified and regularly arranged in anticlinical and synclinal forms according to the structures governing stratified rocks, as shown by their contours in plan . . . . as far as their structure goes, these gneisses have the characters of altered sedimentary deposits."

HANS REUSCH

Dr. Hans Reusch was born at Bergen in 1852. He studied at the University of Christiania where Professor Theodor Kjerulf was his principal and beloved teacher. Together with his friend W. C. Brøgger, of the same age, he became an assistant of the Geological Survey of Norway in 1875, and after the decease of Kjerulf in 1888 Reusch was appointed Director of the Survey.

In younger days he studied principally the geology of western Norway, and his detection of Silurian fossils in crystalline schists exercised a considerable influence on the development of our knowledge of the dynamo-metamorphism. His principal papers on this problem were (the titles translated into English): "Silurian Fossils and Pressed Conglomerates in the Bergen Schists" (1882) and "Bømmel- and Karm-Islands with Environs" (1888).

As Director of the Geological Survey, Reusch delivered a numerous series of valuable geological descriptions of most parts of Norway, from Lister, at the southern point, to Finmarken in the north.

In later years he was especially interested in geomorphological questions. He "detected" the "Strandflat," and Fridtjof Nansen's important work on this phenomenon was dedicated "To Dr. Hans Reusch who first described the Norwegian Strandflat as a distinct geological feature."

As an educator, Reusch published a number of class books of geography, zoölogy, and botany which have been used by many tens of thousands of children in the elementary schools. He further started (1877) the popular Norwegian journal *Naturen*, with the same program as the English periodical *Nature*. He was associate editor of the *Journal of Geology* from 1893 to his death.

He died by an accident (October 27, 1922) at the railway station of Hvalstad, in the neighborhood of Christiania, where he had recently purchased a cottage. The day after moving into his new home he attempted to enter an electric train, just set in motion, but his foot slipped, he fell down, and his skull was fractured.

Reusch was a man of a straight and amiable character, a gentleman in all good senses of the word. He had no enemy, but many, many friends, and during forty years he was my bosom friend.

JOHAN H. L. VOGT

TRONDHJEM, NORWAY

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

Boeke, H. E., and Eitel, W. *Grundlagen der physikalisch-chemischen Petrographie.* Berlin: Gebrüder Borntraeger, 1923. Pp. xi+589, pls. 5, figs. 277. Second edition.

The first edition of this work was reviewed at length in the *Journal of Geology*, XXV, pp. 596–97. The present edition has been entirely re-written by Professor Eitel, and enlarged by nearly 200 pages. As is mentioned in the Preface, the book might well be called "Physical-chemical Principles of Mineralogy and Petrology," since it concerns itself as much with minerals as with their aggregates. Covering so much ground, it is impossible to review it adequately, but since the book is so well known it will be necessary here only to call attention to its appearance in a new and enlarged form.

The arrangement followed is similar to that of the first edition. There are sections on the properties of silicate melts, alterations of minerals, genetic significance of melting points and inversion points of minerals, eutectics, gases in the magma, pegmatitic, pyrohydatogenic and hydrothermal phases of magmatic solidification, and minerals produced by weathering, by sedimentation, and by metamorphism.

The greatest change is in the treatment of certain minerals by systems instead of as individuals. Instead of the minerals of the feldspar-, mica-, amphibole-, pyroxene-, etc. groups, we now have binary, ternary, quaternary, etc. mineral systems.

The book, as is usual for all those issued by Borntraeger, is well gotten up, with many illustrations, on good paper, and with clear print.

Brauns, Reinhard. *Die Mineralien der Niederrheinischen Vulkangebiete mit besonderer Berücksichtigung ihrer Bildung und Umbildung.* Stuttgart: E. Schweizerbart'sche Verlagsbuchhandlung, 1922. Quarto, pp. 225, 3 portraits, 32 figures, and 40 plates, each with 4 photomicrographs in photogravure.

When one sees such a beautiful book as this, one might well wish that we, in this country, could turn out something similar, yet how many institutions would be willing to part with the platinum specimens in their museums to make possible its publication.

While books on mineralogy are not usually reviewed in this column, yet this, treating as it does to a great extent the microscopical characters of minerals

and the geologic history revealed by them, may well be considered as coming in the domain of petrography. The book deals with the minerals of the lower Rhenish volcanic province, represented in the collections of the University of Bonn by 4,210 specimens, of which 1,100 are from the Eifel, 3,120 from the neighborhood of the Siebengebirge exclusive of Finkelberg, and 1870 from the latter locality. Several thousand thin sections were studied, 160 of the most instructive of which are reproduced in photogravure.

Underlying the rocks of this region are the crystalline schists, and while they have nowhere been found in contact with the overlying rocks, they are well represented by inclusions in the Tertiary and post-Tertiary rocks. There are gneisses, mica-schists, and phyllites, derived from original clay sediments.

The first igneous rocks of the region are alkaline rocks of the Middle Devonian, and consist of essexites, alkali-diabases, keratophyres, and quartz-porphyries. These were followed in the Upper Devonian by normal alkali-lime diabases with their tuffs. They are all poor in inclusions, and only the top diabase contains Upper Devonian limestone, but there are no inclusions of the crystalline schists. During the Culm neither eruptive rocks nor tuffs appear. At the end of the Culm began the main folding of the Rhenish schists, but extrusions came at least as early as the upper Middle Devonian. In the latter eruptions, inclusions of Lower Devonian graywackes, sandstones, and schists are not rare, but there are no limestones. The minerals of the inclusions show that there had been a metamorphism of the crystalline schists during the Paleozoic, and the first contact metamorphism was produced by an intruding plutonite. Hydrochemical alteration of some of the minerals followed. Then, at the end of the Carboniferous, came a folding of the rocks and dynamometamorphism, and a second contact metamorphism by an intruding plutonic rock.

The next alteration was pyrometamorphism. A temperature near the melting-point of one of the minerals produced cordierite. The development of alkali-syenites with feldspathoids came before the eruption of the Tertiary basalts, since they are found in these as inclusions. Then came the Tertiary eruptions accompanied by tectonic movements. They began in the Miocene with great gas explosions and the eruption of trachytic tuffs, followed by flows of trachyte, andesite, and finally basalt. All of these rocks are full of inclusions which have been metamorphosed by the magma. Next came eruptions of tephritic rocks, beginning perhaps as far back as early Tertiary and ending after the deepening of the valleys and the deposition of the older loess but before the deposition of the later loess. Gas explosions brought up hauynite-bearing trachyte tuffs. Finally came the post-volcanic processes with the formation of zeolites, carbonates, and opal, and the replacement of silicates in the basalts by carbonates. The last action is shown by the carbonate springs.

Such, in brief, is the history of the region as summarized in the introduction. It was worked out chiefly by a study of the inclusions in the rocks, and indicates what may be accomplished by careful and long-continued study of a single region. The fragments from which it was derived are given under the descrip-

tions of the individual minerals. These mineral descriptions are very complete and form the main part of the book. All of the physical and optical properties of some 300 minerals are given, the modes of occurrence, the formation, the age, and the alterations through which they have passed. Many chemical analyses are given also.

Finally, there is a bibliography of 18 quarto pages and 9 pages of descriptive matter referring to the plates. Not only are the 40 plates with their 160 figures of thin sections well reproduced in photogravure, but the photographs themselves are beautiful examples of photomicrographic work. The whole book represents careful work and presents an unusual mode of deciphering geologic history from little and scattered data by means of the tale told in the thin sections. It is an example well worth following in the study of other regions.

DE LAPPARENT, JACQUES. *Leçons de Pétrographie.* Paris: Masson et Cie., 1923. Pp. 501, pls. 27, figs. 120.

After a short introduction of 20 pages on crystallography and of 24 on optical methods, the various rocks are described. The first part is devoted to the igneous rocks. Here some 33 pages are devoted to the rock-forming minerals, 21 to generalities, with the remaining 141 to the igneous rocks themselves. The author follows Wadsworth by inverting the usual order of things and begins with the peridotites, pyroxenites, and hornblendites. Following in order come the rocks of the gabbro, diorite, and granite families, including the plutonites, vulcanites, and the dike-rocks. The author follows Rosenbusch in the use of the latter term for his hypabyssal rocks. In his second division he takes up the monzonites and the syenites, thus separating the latter from the closely related granites. The third group is that of the nephelite syenites, theralites, and ijolites.

The second section of the book deals with the sediments. First, 40 pages on the materials of the sediments, then 170 on quartz-rocks, lime-rocks, argillites, ferriferous rocks, phosphates, saline rocks, carboniferous rocks, and conglomerates.

The third section consists of 27 pages devoted to metamorphic rocks and metamorphism.

No bibliographic references whatever are given in the book, except acknowledgments under cuts taken from other books.

NIGGLI, PAUL. *Gesteins- und Mineralprovinzen.* Band I. Niggli and Beger. *Einführung. Chemismus der Eruptivgesteine, insbesondere der Lamprophyre.* Berlin: Gebrüder Borntraeger, 1923. Pp. xiv+602, figs. 202.

In this volume, the first of a series, the author has set for himself the problem of bringing together the scattered knowledge of regional petrography, to compare mineral and rock associations, and to work out their physical-

chemical laws. Originally it was intended to begin the series with a volume on magmatic provinces, but when much of the work had been done, it was found advantageous to present first certain fundamental ideas, and to devise a new method for the computation and classification of the magmas.

The book is divided into six parts. The first five are by Niggli—the conception of rock- and mineral-provinces, the general survey of phenomena, magmatic rock- and mineral-provinces, chemistry of mineral associations, and chemistry of the principal magma types. The sixth part on the chemistry of the lamprophyres is by Beger.

Niggli summarizes rock formation thus. The magma, gabbroic, or alkali-gabbroic at the beginning of its activity, consisted principally of silicates and oxides of high melting-point and low vapor pressure and volatilizable with difficulty or not at all. In addition there were contained in the magma certain gases and vapors, the so-called exhalations, which gave it high vapor pressure and reduced viscosity. Magmatic differentiation produced from these substances rocks of different kinds, the kind depending primarily upon three factors—decrease in temperature, pressure, and gravity.

The course of differentiation is about as follows. As the magma gradually cools it eventually reaches the stage of crystallization. From a magma of gabbroic character, the first minerals to crystallize are probably the ferromagnesian minerals and basic plagioclase. When these are withdrawn, the character of the magma changes in the direction of the granitic pole and becomes relatively rich in silica and the alkalies. The newly formed crystals must sink, but in so doing they reach the zone of increased temperature, and they are, at least in part, resorbed. But even if resorbed, the resulting magma cannot again become homogeneous, for the decreased temperature of the upper part would cause a renewed separation of the same material. The equilibrium, therefore, depends upon the temperature as well as upon the composition. But there are other factors to be considered. Assimilation certainly comes into play, especially at first, and the adjacent rocks may be melted.

Four stages are recognized in the crystallization of igneous rocks: (1) the normal crystallization of the usual minerals; (2) the pneumatolytic stage; (3) the hydrothermal stage; (4) the formation of carbonates and the replacement of the earlier minerals.

In the fourth chapter the calculation of the magmas in Niggli's new system is taken up. In some ways it is similar to that of Osann. Niggli says: "Since in the comparison of the mineral paragenesis of the rock-minerals the chemical relationships play an important rôle, it is necessary to find a mode of representation which may be used for either igneous, sedimentary, or metamorphic rocks. The system must be such that it may be easily represented graphically." The author then gives the method of calculation. Essentially it is as follows.

The weight percentages of the various oxides are first computed into molecular numbers and each value is multiplied by 1,000 to eliminate decimals.

The molecular number for Fe_2O_3 is multiplied by 2 and its value is added to that of FeO. The sum of Al_2O_3 (with Cr_2O_3 and the rare earths), (Fe, Mn)O +MgO, CaO (+BaO+SrO), and K_2O+Na_2O (+Li_2O) are recalculated to 100 and are represented by *al* (for Al_2O_3), *fm* (for [Fe, Mn, Mg] O), *c* (for [Ca, Sr, Ba] O), and *alk* (for [Na, K]$_2$O). Small amounts of NiO, CuO, etc., have been previously added to (Fe, Mn, Mg)O.

Further values are given by the ratio of K_2O to the sum of the alkalies in *alk*, and the ratio of MgO to the sum of FeO, MnO, and MgO in *fm*. Also the values for *si*, *ti*, *zr*, *p*, *h*, co_2, so_4, cl_2, s_2, etc., are obtained by reducing their molecular numbers in the same proportions as were the values of *al*, *fm*, *c*, and *alk* when they were reduced to 100.

Finally, *qz*, the quartz value, is determined by a computation which also gives roughly the mineral composition. The minerals with highest SiO_2 contents are the feldspars, augite, and hornblende. Taking the simplest formulae, we have for orthoclase: 1 *alk* (K_2O), 1 *al*, and 6 *si;* for albite the same with Na_2O substituted for K_2O; and for anorthite 1 *c*, 1 *al*, and 2 *si*. The values used in theoretical augite and hornblende are 1 *fm*, 1 *c*, and 1 *si*. If $al>alk+c$, the remaining *al* is united with *si* as sillimanite. If $alk>al$, the excess *alk*, with high *si* content of the rock, usually goes into aegirite. If there is an excess of *si*, it is usually in the form of quartz; if a deficiency, then minerals with less SiO_2 are to be expected, namely olivine, biotite, feldspathoids, ores, etc. The *qz* value, therefore, represents the excess of silica over that required by the first group of minerals (*si'*), therefore

$$qz=si-si'=si-\{6\ alk+2(al-alk)+[c-(al-alk)]+fm\}$$
$$=si-(100+4\ alk),\ \text{when}\ alk<al.$$

When $alk>al$, then

$$qz=si-(100+3\ al+1\ alk).$$

A few samples will show the method of computation.

A diorite from Tuolumne River, Sierra Nevada, California, gives $si=171$, $al=34.5$, $fm=28.5$, $c=24$, $alk=13$. Therefore, $si'=152$, and $qz=171-152=19$. Some quartz, but not much, is to be expected.

A diorite from Lavia, Finland, has $si=134$, $alk=12$, $si'=148$. The quartz value is -14, which may be accounted for by the presence of magnetite or of aluminous augite or biotite without the need of olivine or nephelite.

An olivine gabbro from Molkenhaus, Harz, with $si=91.5$, $al=16$, $fm=61.5$, $c=18$, $alk=4.5$, $si'=118$, gives $qz=-26.5$, accounted for by the presence of olivine.

An urtite from Lujavr Urt, Kola, has $si=113$, $al=40$, $fm=9$, $c=3.5$, $alk=47.5$. Here $alk>al$, $3\ al+1\ alk=167.5$, and $si'=267.5$, giving $qz=-154.5$, consequently a mineral with a low silica content, such as nephelite, must form an essential constituent.

So much for the calculations.

Very useful tables are given showing silica-rich and silica-poor minerals, and combinations of minerals which may, with the same chemical composition of the magma, occur in the place of other combinations of minerals, the latter a valuable object lesson showing why a mineralogical classification is of more value from a genetic standpoint than one entirely chemical.

Niggli says: "One basis of the present classification is purely chemical, giving a classification of magma types. But it differs from the American (meaning the CIPW) classification in that the divisions are natural. The three important factors in a natural classification are magma provinces, composition, and physical conditions of magma cooling." He thinks a binary nomenclature is best. The subdivisions of the magma will be most precise on a chemical basis, but the rock names should retain their mineralogical significance. He would modify the mineralogical rock names by an adjective expressing the magma type. The third ideal point, the physical conditions of magma cooling, finds expression in structural or textural relationships.

In chapter v the magmas are classified in three main series, the alkali-lime, the soda, and the potash. The former, which is most widely distributed, is subdivided into the granitic, dioritic, gabbroic, and ultra-femic magmas, and these are again subdivided, giving, for example, under the granitic magma group of the lime-alkali series the *magma* types aplite-granitic, engadinitic-granitic, yosemitic-granitic, normal-granitic, granodioritic, and opdalitic. That the chemical composition is the dominant factor for Niggli is shown by his statement on page 97 that "nearly all typical granites show in thin sections, usually a predominance of plagioclase over orthoclase." The reviewer would not class such rocks among the granites.

The following 90 pages are devoted to individual magma types, and there are given many analyses recalculated into *si*, *al*, *fm*, *c*, *alk*, *k*, and *mg* values. Among these rocks is given the term yentnite (p. 121) which should be omitted, since it was withdrawn by Spurr in 1908 when it was shown that the so-called scapolite was quartz. The name yogoite, also, on page 188, was withdrawn in 1896 by Pirsson since the original type was found to be, not a syenite, but practically identical with Brögger's monzonite. There is, however, a place for the term yogoite, since another rock, also found on Yogo Peak, and called shonkinite, has the actual composition required by the definition of yogoite. Even in his mineralogical classification, Niggli stresses the chemical side. Thus he says that granodiorite, as defined by Lindgren, is incorrect in principle, for the potash feldspar may contain soda, or there may be potash in the biotite. But Lindgren's definition belongs to a mineralogical classification of rocks, and so should not be criticized if it does not fulfil the requirements of a combined mineralogical and chemical classification. Further, it seems to the reviewer incorrect to redefine rocks, which in the original definition depended upon composition, in terms of chemical composition. Shonkin-

ite, originally defined as a quartz-free, orthoclase rock with more dark constituents than light, is redefined on page 192 as a rock with predominant potash and with abundant (he does not say dominant) dark constituents.

The final chapter by Beger, containing 360 pages, is devoted entirely to the lamprophyres, and 382 analyses are recalculated. May all other rock types be treated as elaborately as this one!

It is, of course, impossible in a review to give all features of a textbook in detail; here only an attempt has been made to give an outline. Without question, it is one of the most important recent contributions to the science. That such a high class, specialized, and extensive work should be issued in these days of high cost of printing is a great credit to the publishers.

REVIEWS

Geologic Structures. By BAILEY WILLIS. Pp. xi+295, pls. 10, figs. 121. McGraw-Hill Book Company, New York, 1923. Price $3.50.

Structural geology, dealing largely with the operation and manifestations of earth forces which are as yet imperfectly understood, has necessarily been slower in developing than some other phases of our science. The processes and factors which enter into the problems of earth deformation are so complex and variable that most of the notable advances in this far-reaching field have fallen to a few outstanding leaders. A few works like the classic *Mechanics of Appalachian Structure* form the pillars of the structural edifice. Now, after many years of ripening experience, Professor Willis has favored us with a more general treatise on structural geology.

Geologic Structures is a textbook intended to fill the needs of both elementary and advanced university students. As such, every effort has been made to avoid as far as possible the use of complicated technical terminology, and to present the subject simply, "in English rather than in Geology." This seems to the reviewer most commendable from every viewpoint, for so commonly the real depth of investigative insight is found to vary in some inverse relation to the fondness for technical nomenclature. Some simplification is accomplished by treating the subject in two sections. The first is given over largely to the description of rock structures, irrespective of theoretical considerations, and is thus measurably independent of the more involved concepts of earth dynamics and the more controversial philosophical aspects of the subject. The second section is an analysis of the mechanics of rock deformation and the methods of field interpretation.

The chapters of the first section are devoted to stratification, folds, joints, structures of igneous rocks, and faults. The descriptions are clear and concise and the matter well chosen, but with the possible exception of the chapter on faults, the reviewer would welcome a somewhat fuller treatment. For parallel folds Willis has substituted concentric folds, which seems a better use of terms. Anticlinoria and synclinoria as composite folds would seem to merit rather more discussion

than is given them. A pure description of joints detached from the involved forces and mechanics of formation does not afford great possibilities, hence this chapter is very brief. Further treatment of joints, however, appears in the discussion of the mechanics of rock deformation. But the brief chapter of three-and-a-half pages on structures of igneous rocks is not supplemented by further consideration of the genetics.

Faults are described in much greater detail, and more that is new has been introduced here. Unusually complete treatment has been given to the mechanical effects produced upon the slipping fault surfaces, such as scratches, striae, furrows, grooves, chatter marks, mashing, plucking, jointing, gouge, breccia, gash veins, and drag. A very happy advancement is the grouping of faults as high-angle and low-angle. It is often difficult to distinguish a tension fault of steep inclination from an upthrust fault, and, on the other hand, "normal faults may curve out from the steep attitude which they commonly assume and approaching a horizontal position may simulate thrusts." In the absence of positive evidence, which frequently is not available, it is often unwise to commit one's self as to the thrust or tension character of a given slip. When the true character of the faulting remains uncertain, it is therefore highly desirable to have noncommittal terms which nevertheless classify faults according to one of their most significant genetic characteristics. Such is the grouping into high-angle faults and low-angle faults.

The geologic profession has commonly manifested a predilection for assuming tension faults in preference to thrust faults in cases where the true character is not evident. Willis points out, and emphasizes, the fact that the observed field facts in many cases may be as well explained by thrust faulting as by tensional faulting. As time goes on there is likely to be considerable revision of present interpretations in many important instances.

The geometries and nomenclature of faults receive careful treatment. But in a book where clear thinking is put to the fore, and where technical terminology is subordinated to the real flesh and blood of the subject, the reviewer regrets to find the continued use of that abomination of all fault terms—the hade. The physiographer describing the slope of a land surface, the railway engineer considering the grade of his track, the stratigrapher and structural geologist reading the dip of strata, all measure from the horizontal. If one is to keep clearly in mind the angle of slope of the land surface, the angle of dip of the strata, and the angle of inclination of the fault plane, it is a most unfortunate complication to measure the first two from the horizontal and the last from the vertical. An angle of

30° should call to mind the same slant, whether applied to slope of surface, dip of strata, or dip of a fault plane. Thinking in terms of high-angle faults and low-angle faults has been an emancipation from the confusions imposed by the idea of hade, and it seems unfortunate that such a concept as the hade, with its capacity for mischief-making, should be retained, though, to be sure, such is the present orthodox usage.

The more analytical and philosophical aspects of the subject are brought together systematically in a long chapter entitled "Mechanics of Rock Deformation." The nature of earth forces and the modern conceptions of the behavior of rock material under deformative stress are admirably presented. With sound ground-work laid, Willis proceeds from these working principles to an analysis of fracture, an analysis of competent and incompetent folding, and an analysis of shear and flow. The principles of competent and incompetent folding have been particularly associated with the name of Willis ever since the appearance of his *Mechanics of Appalachian Structure.* Competent folding is described as that

> . . . . Produced by compression in the direction of the undisturbed stratification, and which is conditioned by the requirement that a rising arch shall lift the load, or a sinking syncline shall displace the underlying material. . . . . Incompetent folding is the result of a deflecting pressure which is initially directed at right angles to the strata, or nearly so, when they are in a horizontal or gently inclined position. . . . . The essential fact in the development of an incompetent fold is that there has been subsidence in response to the attraction of gravity or there has been uplift due to one or another of several kinds of up-pushing.

A geosyncline, a broad uplift like the Colorado Plateau, or the coverings of batholiths and laccoliths are classed as types of incompetent folds. As used by Willis, competent and incompetent folds differ markedly in the mechanics of growth. This is a more basic distinction than the differences involved in the behavior of relatively competent and relatively incompetent layers in the development of a given fold or folds.

In the analysis of shear and flow the key method is the resolution of forces. In this way the operation of the deforming stresses is well pictured and understood. Various specific rock problems have been introduced and solved diagrammatically by this method. These give the student excellent practice in interpreting jointing, shearing, and schistosity. The strain-ellipsoid method is also considered and utilized in a somewhat subordinate way. Many geologists, however, may prefer the method of the strain-ellipsoid as being simpler, and affording a more

concrete and perhaps more complete picture of what has taken place, portraying particularly well the interrelations of tensile and compressive stress, shearing, fracture cleavage, and flow cleavage.

"Field Methods," the culminating chapter, is a delightful glimpse into the workings of Willis' own mind when called upon to face a variety of new problems as have so often confronted him in his world-wide field experience. The beautiful, artistic touch of the poet has aided much in bringing out the wisdom and advice of the sage. The spirit of Willis is there in all its charm. Physiography as a key to the interpretation of structure, and, as evidencing and measuring diastrophic changes, is but one of the visions opened up in this stimulating chapter. It should lead the student to emulate the breadth of vision of the author.

The final chapter, "Graphic Methods and Practical Problems," by Robin Willis, is an excellent presentation of methods of determining the strike, dip, and thickness of strata, and of the principles of normal and isometric projection. Seven practical problems with solutions illustrate the application of normal projection to structural studies. This treatment of methods will be found very useful. Three appendixes, the last comprising ten plates of folding experiments (from the *Mechanics of Appalachian Structure*) with descriptions and discussion of results, complete the volume.

In *Geologic Structures* Willis has accomplished his avowed aim of meeting the needs of both the untechnical reader and the special student of structural and dynamic geology. The former will welcome the sharp descriptions and clear presentation of the essential facts; the latter will grasp with enthusiasm the results of the special researches of Willis upon fundamental principles, the abundance of new material and illustrative matter, and particularly the methods and spirit of this able leader of geologic thought.

R. T. C.

Gypsum: Its Occurrence, Origin, Technology and Uses. By FRANK A. WILDER. Vol. XXVIII, Iowa Geol. Survey Annual Reports for 1917 and 1918, with Accompanying Papers. Published 1923.

With the exception of a few pages devoted to statistics of mineral production of Iowa in 1917 and 1918, this entire volume is given over to a monographic study of gypsum, including special chapters devoted to the Iowan gypsum deposits. The volume is the outgrowth of Dr. Wilder's unusually intimate knowledge of the gypsum industry developing

through a twenty-five-year period, which embraced several years of service with the Iowa Geological Survey and many years experience as a producer of gypsum and as president of the Southern Gypsum Company, Inc. Dr. Wilder is to be congratulated upon the completion of what is unquestionably the most complete and comprehensive report on the subject of this important mineral resource that has ever been issued.

Of special interest in the chapter on "Physical and Chemical Properties of Gypsum" are the statements that in Nova Scotia veins of crystalline gypsum-selenite—8 to 20 feet thick and extending for half a mile along the strike of the gypsum beds, have been reported. "Satin spar," or fibrous gypsum, is interpreted as a deposition along cracks and crevices and in cavities, and in some cases, it is stated that the pressure created by the growing fibrous crystals appears to have developed cracks several inches across. Conclusive evidence of such action is not, however, presented. The veins of satin spar are characterized by a longitudinal "parting" similar to that developed in most asbestos veins.

Chapter ii reviews briefly the important occurrences of gypsum in the United States and foreign countries, and gives a map showing locations of the developed and undelveloped deposits of the United States. A valuable table classifies the American and foreign deposits according to geologic age, and it is noteworthy that deposits in the Punjab, in India, are reported to be Cambrian. The deposits yielding most of the United States supply are Silurian and Mississippian and the European supply comes mainly from Permian and Triassic beds.

Chapter iii is devoted to the "Origin of Gypsum and Anhydrite," and is of especial theoretical interest. That gypsum in thick beds comparable to those worked commercially is the result of somewhat unusual combinations of circumstances is evidenced by the fact that no such deposits are known to be forming today. The present-day deposits are either very impure or if pure consist of only thin beds interpolated with other sediments. Any hypothesis offered to explain the origin of gypsum and associated commercial salts must take account of the very considerable thicknesses sometimes involved, over 1,000 feet at Strassfurt and over 3,000 feet at Sperenburg, Germany. In the evaporation of sea water, three-fourths of the gypsum is deposited when the volume of water has been reduced from 80 to 92 per cent. The remaining one-fourth is deposited with sodium chloride but constitutes such a small part of the precipitate that the commercial value of the salt is not impaired. To produce only 15 feet of gypsum from the evaporation of ordinary sea water, assuming a basin with vertical walls, would require a depth of

nearly 35,000 feet of sea water. Depths of this order are not to be expected in epicontinental seas, and to avoid the necessity of such a supposition, E. B. Branson postulated that the basin where precipitation was in progress was supplied not from the open ocean, but from other basins where a lesser degree of evaporation had been in progress. Even under such a modified theory of marine deposition, the depth of water necessary must be great, for enough water must be present to hold in solution all of the sodium chloride, that is, the volume of water must not have been reduced below one-tenth that of normal sea water. To deposit 10 feet of gypsum under this modified hypothesis, the sea would have to be at least 1,400 feet deep. Branson avoids the necessity of assuming excessive depths of sea water by appealing to the transport of gypsum by marine currents as the agency by means of which excessively thick deposits have been accumulated.

A second difficulty in the way of the marine-evaporation hypothesis arises out of the calcium carbonate content of such waters. The investigations of Julius Stieglitz appear to show that calcium carbonate deposition must have preceded and accompanied gypsum deposition under any theory of deposition from sea water, even when due allowance has been made for possible variations in the calcium carbonate content of the atmosphere and for the effect of other salts in solution. Yet many thick deposits of gypsum are, according to analyses, essentially free from calcium carbonate, and gypsum beds seem seldom to be underlain by limestone.

A third possible conception, that thick gypsum deposits have resulted from the evaporation of inland lakes fed by ordinary fresh-water streams, is regarded by Wilder as offering fully as many difficulties as the hypotheses of marine evaporation.

Dr. Wilder's contribution to the genesis of gypsum deposits relates primarily to the Iowan beds. In the Fort Dodge area of Iowa there is an average of about 15 feet of gypsum. If this had been deposited by the evaporation of sea water, there should be presumably a bed of limestone 1 to 2 feet thick below it, but no such limestone exists, although considerable calcium carbonate occurs as an impurity in the gypsum. Dr. Wilder advances the hypothesis that the gypsum of these deposits is not the result of marine evaporation, but was deposited in a restricted basin fed by streams exceptionally rich in calcium sulphate. Certain layers of the St. Louis limestone contain nearly $2\frac{1}{2}$ per cent of gypsum and some gypsum is present throughout this formation. The Coal Measure shales about Fort Dodge abound in crystals of selenite, as do also the marls

about the Ste. Genevieve formation. Gypsum, Wilder believes, was taken into solution abundantly in surface and ground waters from land surfaces where the foregoing formations were exposed and was redeposited in the evaporating waters of an enclosed basin.

Chapters iv and v of the report deal in detail with the Iowa occurrences, and Chapter vi deals with the "History of the Gypsum Industry."

Chapters viii to xxi and Appendixes I to VIII, constituting more than half of the volume, are devoted to an exhaustive consideration of the technology of gypsum, the testing of gypsum and gypsum deposits, etc. The report closes with more than 250 references dealing with gypsum.

E. S. B.

Elementary Crystallography. By J. W. EVANS and G. M. DAVIES. London: Thomas Murby & Co., 1924. Pp. vi+134, figs. 181. 9*s*. 6*d*. net.

The authors are to be congratulated for having stated the essentials of crystallography in such simple, clear language in this small volume. Photographs of crystal models, rather than the old-fashioned line sketches used, would be more in keeping with the style of the text. The orthorhombic system is covered first. It seems that the short descriptions of the stereographic and gnomonic projections, and chapter xv on the thirty-two crystal classes, could better have been omitted from such a work.

D. J. F.

West Virginia Geological Survey: Tucker County. By DAVID B. REGER. Wheeling, W. Va.: 1923. Pp. xviii+542, pls. 16, figs. 11, maps 2.

Elaborate and detailed reports on areal geology in some instances suffer from a lack of organization of the material or the want of a full index. On this account the reader wishing information upon some particular point may be forced to search through many pages of other matter. Among the merits of this report on Tucker County not the least are its commendable arrangement, its clear separation of fact from theory, and the inclusion of its complete Table of Contents and Index.

Structurally, the region is divided into two somewhat sharply contrasted parts. The western portion, composed of less competent Devonian strata, has undergone severe folding, producing steep dips, while in the eastern portion, where the Mississippian and Pennsylvanian strata are more competent, the folds are broad and symmetrical and the dips low. The attitude of the beds is indicated by structure contours, and

by three cross-sections which are confined to the more strongly folded western portion.

Detailed treatment of the stratigraphy begins with the youngest series represented, the Monongahela, and concludes with the oldest, the Portage. Attention is called to radical changes in the correlation of certain coals. The "Davis" coal is found to be the representative of the Upper Freeport coal, and not of the Lower Kittaning, with which it had been provisionally correlated. The "Thomas" seam, 190 feet higher, is the Bakerstown coal of the Conemaugh series, and not the Upper Freeport at the top of the Allegheny series, as formerly supposed.

A valuable contribution to our knowledge of the animal life of Mississippian times is the discussion by Dr. George H. Girty of the faunas of the Greenbrier limestone. The term "Greenbrier limestone" had not heretofore been adequately defined paleontologically. The upper part of the Greenbrier is obviously of Chester age, and although it would be interesting to know which of the numerous subdivisions of the Chester it represents, Dr. Girty considers more important a determination of the age of the lower part of this formation. He reaches the conclusion that the basal part of the Greenbrier, even certain beds containing *Lithostrotion* (considered diagnostic of St. Louis age), belongs to the St. Genevieve epoch. The presence of a basal unconformity supports this view.

A. H. B.

TUCSON, ARIZ.
March 4, 1924.

Geology of a Portion of the Badlands. By FREEMAN WARD. *The Paleontology of the Area. The Badlands as a National Park.* By W. C. TOEPELMAN. *South Dakota Geological and Natural History Survey*, Bulletin 11, 1922. Pp. 80, pls. 16, figs. 11.

The Badlands of South Dakota are justly famous as a collecting ground for vertebrate fossils. Former work done in the region has been largely paleontologic, and relatively little attention has been given to geologic problems. The present publication is a detailed geological study of a definite area which has been chosen because it is considered typical of the whole, and because of a belief in the possibility of oil production therein.

Probably the most interesting part of the report is that which discusses the origin of the formations, particularly those of Oligocene age. Prefacing this discussion is a tabulation of the facts to be accounted for, striking among which are (1) alternation of two main materials, pink shale and grey sandstone; (2) absence of bedding planes; (3) absence of potash.

The high soda content and deficiency of potash in the sediments, according to analyses given on page 21, is put forward as a strong argu-

ment in favor of the theory of their derivation from the Black Hills where soda-rich igneous rocks predominate. These analyses are evidently not of a high order of accuracy. It has recently come to the attention of the reviewer that a serious error has been made, later analyses showing soda and potash to be present in about equal amounts.

The hypothesis that the alternation of sandstone and shale is due to a repeated change of climatic conditions is considered but is dismissed as improbable. The interpretation favored by the author is an alternation of crustal stability and uplift.

Harold R. Wanless, in "The Stratigraphy of the White River Beds of South Dakota" (Proc. Am. Phil. Soc., 1923), takes exception to this view of intermittent and recurrent uplift, and expresses the opinion that "the sudden changes in the character of the sediment . . . . can best be interpreted as the result of climatic change." He discusses critically the successive interpretations given to the climate and physiography of White River time by geologists of the past seventy years. Dutton and Hayden held that the White River sediments were of lacustrine origin, while this theory has been rejected by Mathew, Johnson, and Hatcher. Ward has now revived the lacustrine theory in a modified form.

A. H. B.

TUCSON, ARIZ.
March 4, 1924

Kartbladet Gran. Av OLAF HOLTEDAHL og JAKOB SCHETELIG. With summary in English. Norges Geologiske Undersökelse, Nr. 97. Kristiania, 1923. I Kommision Hos H. Aschehoug and Co.

Om Vegetationsforsok med Glimmermineralerne Biotit og Sericit som Kalikilde. Av B. HANSTEEN CRANNER. With summary in German. Norges Geologiske Undersökelse, Nr. 114. Kristiania, 1922. I Kommission Hos H. Aschehoug and Co.

Undersökelser over Norske Lerer, I. Av J. v. KORGH. With summary in English. Norges Geologiske Undersökelse, Nr. 115. Kristiania, 1923. I Kommission Hos H. Aschehoug and Co.

Undersökelser over Norske Lerer, II. Av BRYNJULF DIETRICHSON. With summary in English. Norges Geologiske Undersökelse, Nr. 116. Kristiania, 1923. I Kommission Hos H. Aschehoug and Co.

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